A METHODOLOGY FOR COMPREHENSIVE STRATEGIC PLANNING AND PROGRAM PRIORITIZATION

A Dissertation
Presented to
The Academic Faculty

By

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In Partial Fulfillment
Of the Requirements for the Degree
Doctor of Philosophy in Aerospace Engineering

Georgia Institute of Technology

August, 2008

A Methodology for Comprehensive Strategic Planning and Program Prioritization

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Date Approved: May 14th, 2008

ACKNOWLEDGEMENTS

First, I would like to thank my advisor, Dr. Dimitri Mavris, for guiding me through this process and for believing in me when I don't know how much I even did. You have given me so many opportunities for which I will always remain grateful.

I would like to thank Dr. Kirby for the immeasurable amount of help and guidance which she has provided to me over the past 6 years. It was an honor and a privilege to work with her and develop not only as a student but also as a person. Thank you to Dr. Schrage for his great assistance and feedback in the formulation of this thesis from a vague idea to the final work. Thank you also to Dr. Bishop and Dr. Costello for their participation in my thesis committee and the feedback and comments they provided.

I would be remiss if I did not also thank all my colleagues who have provided great help through the development and application of this work. I would particularly like to thank Livia Carneiro, Elise Beisecker, Brett Tuley, Curtis Iwata, and Scott Wilson for their contributions to various aspects of this process.

Finally, I would like to thank my family and friends who have supported me for many years with their love and support and without whom I never would have completed this long, and sometimes winding, road. Thank you to my parents for their encouragement both in my recent pursuits and also for instilling me with a love of learning and accomplishment. I would like also like to attempt to show my gratitude to my wife Katie, to whom I can never fully express my thanks for the level of support and encouragement with which she has provided me. I never would have achieved this without her.

Thank you!

Chris Raczynski

Atlanta, GA

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NOMENCLATURE

AHP	Analytic Hierarchy Process
CM	Creative Management
CV	Cumulative Voting
DoD	Department of Defense
DSS	Decision Support System
GAO	Government Accountability Office
IPPD	Integrated Product and Process Development
MADM	Multi-Attribute Decision Making
MCL	Master Capability Library
MODM	Multi-Objective Decision Making
MOGA	Multi-Objective Genetic Algorithm
M&S	Modeling and Simulation
NASA	National Aeronautics and Space Administration
NAVSEA	Naval Seas Systems Command
OEC	Overall Evaluation Criterion
ONR	Office of Naval Research
QFD	Quality Function Deployment
S3	Ships and Ship Systems
SBU	Small Business Unit
SME	Subject Matter Expert
SOAR	Strategy Optimization for the Allocation of Resources
SWOT	Strengths, Weakness, Opportunities, and Threats
S&T	Science and Technology
TIES	Technology Identification, Evaluation, and Selection

TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TRL	Technology Readiness Level
UPS	United Parcel Service

SUMMARY

Changes in the global economy are making the world a smaller place and companies are finding themselves competing in new markets. With this change it is becoming necessary for the organizations to plan further into the future and with greater structure than they have in the past. In addition to the corporate changes, government agencies are being required to meet their mandated objectives with ever decreasing funding. In both situations a new methodology is needed which will allow the planners and decision makers to align their program and technology investments with the vision for the future.

This process, Strategy Optimization for the Allocation of Resources (SOAR), is a strategic planning methodology based off Integrated Product and Process Development and systems engineering techniques. This methodology provides the framework for strategic planning and resource allocation. Utilizing a top down approach, the process starts with the creation of the organization's vision and its measures of effectiveness. The top level measures of effectiveness are prioritized based on their application to external world scenarios which will frame the future. The programs which will be used to accomplish this vision are identified by decomposing the problem. Information is gathered on the programs as to the application, cost, schedule, risk, and other information which the decision maker deems necessary. The relationships between the levels of the hierarchy are mapped utilizing subject matter experts who have knowledge and expertise in the areas involved. These connections are then utilized to determine the overall benefit of the programs to the vision of the organization. Through a Multi-Objective Genetic Algorithm, a tradespace of potential program portfolios can be created amongst which the decision maker can allocate resources. The information and portfolios are presented to the decision maker through the use of a Decision Support System which collects and visualizes all the data in a single location.

This methodology was applied to an example problem based on a science and technology planning exercise conducted by the Unites States Navy. Utilizing several high level Naval Vision documents, the capabilities and world scenarios for possible missions in a 20-30 year timeframe were identified. A thorough decomposition was defined and technology programs identified which had the potential to provide benefit to the vision. The prioritization of the top level capabilities was performed through the use of a rank ordering scheme, and a previous naval application was used to demonstrate a cumulative voting scheme. In order to capture the relationships between the various levels of the hierarchy, experts were brought together in two workshops where the Nominal group Technique was used. Interrelationships between the technologies were identified which would affect how these programs could be combined together into portfolios. A MOGA was utilized to optimize portfolios with respect to these constraints and information was placed in a DSS. This formulation allowed the decision makers the ability to assess which portfolio could provide the greatest benefit to the Navy while still fitting within the allocating funding profile. The use of this application proved that the methodology as outlined was simple, traceable, and rigorous in the creation of a strategic plan.

CHAPTER 1

MOTIVATION

Changing Corporate Environment

The environment in which corporations do business is vastly changing in the modern world. With the improvements in communication technology, increased shipping capabilities, and the willingness of governments to open their markets to new goods, the world is becoming a much smaller place. Competing in this environment can be a challenge for some companies and a great opportunity for others. How they choose to react will determine whether they remain relevant or fade into obscurity.

Globalization

The new era of the global economy has become a reality. More and more companies are competing not only with their traditional, domestic rivals but now also new ones from overseas. These new ‘global industries’ are defined by Michel Porter as ones, “in which the strategic positions of competitors in major geographic or national markets are fundamentally affected by their overall global positions.” (M. E. Porter 1980) With the rise of threats from new oversees competitors there is also an accompanying rise in opportunities for those companies which are willing to take a risk. One company which reorganized itself in the shrinking world is United Parcel Service (UPS). It expanded its international small package service over a 15 year period by successfully predicting a rise in demand. UPS CEO, Mike Eskew, states that in order to create solutions for customers “you have to prepare for what they need in five or ten years from now, too, and that takes research, effort, and scenario planning.” (Eskew 2007)

There are many advantages to participating in the global market. From an R&D standpoint, there are many projects which require such large amounts of capital that only the added revenues of going global can make the decision to launch them viable. Possibly the largest benefit is from the "Economy of Scale" which is the idea that the more items that are produced, the cheaper they are to make. By taking advantage of globalization to expand internationally, the number of units produced will increase such that production costs are greatly lowered. These reduced costs help in overseas markets as well as provide benefits domestically with the ability to lower prices while still maintaining profit levels (M. E. Porter 1980).

Disadvantages to the global market must also be taken into account by organizations. The needs of the consumers may be sufficiently diverse enough that a company will need to market or produce slightly different products based on location. Possibly one of the most severe restrictions on globalization by the aerospace industry is the differing governmental policies across the globe. For instance, some technologies developed in the United States are barred from being exported to select countries based on export control law. Additionally, the environmental laws differ such that products might meet emissions or noise regulations in some countries but not others. All of these issues must be addressed and understood in order to be able to compete in these new global markets.

Globalization carries with it many capital costs which must be accounted for by an expanding company. Foreign field offices, indigenous workers, and increased long distance communication are just some of the myriad of elements which must be understood. This planning is not simply a "do it" or "don't do it" decision but, rather, striking the proper balances in order to accomplish the organization's goals while only spending the necessary capital. One of the most striking things about the global economy is the number of options available to international companies. Where should a new product be marketed? Where should manufacturing occur? These questions can have a myriad of possible answers, but it is up to management to properly weigh the various options and come up with the business plan that best suit the needs of the company.

Technological Advancement

The environment of technology research and development is changing. This is evident as the percentage of total U.S. research that is conducted by industry has increased from 67% in 1970 to 74% in 1997 (Jankowski 1999). Funding by the top 100 U.S. companies in terms of money spent on research rose 15.4% between 1998 and 2005. Several aerospace companies are included in this list and have shown marked increases in the past 8 years. Of particular note are Lockheed Martin which increased its R&D expenses by 9.5%, General Electric by 74.7% and Northrop Grumman by 185% (Crawford and Whiteley 2006). This increased emphasis on industry led research means that there is less basic science and more applied sciences. Companies are generally only willing to pay for R&D which can directly benefit their products or services. This puts increased emphasis on technologists to ensure that the programs that are proposed fall well in line with the overall vision of the organization.

Resources which are spent on research and development do not directly provide profit to the company, so it is imperative that this money is spent on products which show the most promise and benefit for the cost. Research also provides great opportunities for corporations because the first one to bring a new or better product to market has a distinct advantage over competitors. However, this comes with a distinct risk since the final outcome of R&D projects can fall well short of the prediction. The best chance a company has in exploiting technology while minimizing risk is to ensure that the portfolio of programs being pursued is robust and well planned. Robustness in a technology program means that the programs perform well, independent of the world environment.

Changing Government Environment

The aerospace industry includes both corporate and government entities. Many of the same issues involving technological advancement and global competition are applicable in this area as well. The Department of Defense (DoD) has many organizations which pursue research and technology programs for the various armed services including the Office of Naval Research (ONR), Air Force Research Lab (AFRL), and Defense Advanced Research Projects Agency (DARPA). The National Science Foundation (NSF) and National Aeronautics and Space Administration (NASA) are civilian agencies which also fund and perform a great deal of aerospace related research. While the measure of benefit and value is not profit, as it is in the corporate environment, these organizations sill must provide rationale for the funding and resource allocation decisions that are made.

Increasing Accountability

The current trend in the United States government is the focus on accountability and traceability. The Government Accountability Office (GAO), formerly known as the General Accounting Office, is the agency within Congress tasked to provide "oversight, insight, and foresight" to the federal government. The current Comptroller General (CG) of the United States and head of the GAO, David Walker, was appointed in 1997 and since then, has stressed the need for strategic planning and minimizing the waste of resources within the government.

Assessing where government agencies are in terms of measuring the outcome of programs is what CG Walker says is of main importance in increasing accountability. According to Walker, a cohesive set of performance measures ideally should be created that "can be used in connection with all the strategic planning efforts of all the different departments and agencies within the U.S. government" and "those measures can then be used to communicate a better and more balanced scorecard on the performance of the government (Tidrik 2005)." This need for accountability is evident on the civilian side of the government. In 2002 members of Congress chided the National Science Foundation on "whether the NSF has a satisfactory process for prioritizing multiple competing large-scale research facility projects (Committee on Setting Priorities for NSF-Sponsored Large Research Facility Projects 2002)."

The Department of Defense (DoD) is also of concern since it annually gets $400 billion worth of funding and rates a "'D' in terms of economy, efficiency, transparency, and accountability," according to Comptroller Walker. This is changing, however, as the Congress and American people demand better accounting of government spending, "Our country cannot afford to waste resources, much less billions of dollars each year." (Tidrik 2005) In a September 2006 report on military technology research, the GAO also remarked that "from a strategic perspective, the department lacks strong influence at the corporate level to guide the department's technology investments." (Government Accountability Office 2006) It is clearly evident that government agencies must reform their technology and program resource allocation process to ensure to the American people that their money is being spent in the right locations.

Decreasing Federal Research

Since the "Golden Age of Science" of the 1960's, the federal government has decreased its funding of R&D. In particular, between 1987 and 1997 federal research funding decreased at a rate of 2.3% per year (Jankowski 1999). A decrease in available funding leads to increased competition amongst those organizations which perform the technology research. This competition requires those pursuing the funds to prove the benefits their program has to the requesting agency. This competition is also combined with the requirement for better accountability within the government which leads to a new paradigm of cooperation between the government funding source and the research provider. Cooperation of this scale ensures that both organizations are concentrated on establishing the worth of the program to the government agency’s needs. These competitive changes in the world market demand a new shift in the methods used for planning and resource allocation.

The Need for a New Method

Planning is essential to surviving and excelling in the new global environment, whether the organization is a company in pursuit of profits or a governmental agency pursuing knowledge and advantage. Such a plan requires the elements of vision, connection to goals, and knowledge based resource allocation in order to effectively link the portfolio of programs to the direction and guidance of the top level organization management.

Vision

Vision is the organization’s view of where it will be in future in terms of its market, size, and accomplishment. Comptroller General Walker states that without a plan with vision, “any road will lead you to where you’re going since you don’t know where you’re going (Tidrik 2005).” According to Sharon Nelton, vision “defines what an organization has been established to accomplish, delineating products and markets and, in some instances, going further to state a company's creed or values, its operating philosophy, or its major goals. (Nelton 1994)” Setting goals and milestones to be reached within a certain timeframe will keep the organization focused on what it wants to accomplish and by what date. Planning does not necessarily have to encompass every level of an organization but can be performed by any unit which needs to identify a way forward.

Vision, which takes place at the highest level of management, focuses on where the company or organization as a whole is headed in the world environment. Gary Hamel, lecturer at the London Business School, and C.K. Prahalad, professor at the University of Michigan, have termed this level of vision “Strategic Intent”. At this level of the organization the focus is on what markets are of the greatest importance and what global position should be taken. While the vision may originate at the top of the organization, Prahalad and Hamel point out that the best way to achieve the goals at this level is to ensure that the whole of the organization is within the communication loop. Shelton agrees, “[Vision] enables different groups within a company—marketing, finance, merchandising, human resources, and the like—to have not only a similar vision but also similar expectations.” Only when everyone from the CEO to the worker on the floor understand and believe in the strategic intent can it be accomplished.

Planning, which takes place at lower levels of the organization such as Small Business Units (SBUs) or divisions of the overall government agency will have a much smaller scope than those employing Strategic Intent. Here the focus will be much more concentrated and likely better defined. The resulting programs will be more numerous but also increasingly well laid out. While the plan here should be based on the smaller unit’s vision, there must exist some type of linkage up to the higher levels of the hierarchy in order to ensure that one group does not stray from the vision of the overall organization.

Linked Hierarchy

The second element of a solid plan is the connection of the goals and objectives of the various levels of the organization. Top level vision elements are the highest goals of the organization and, as such, are broad in scope. Linking the impact of programs or technologies to that level would be very difficult due to the fact that it is relating something very specific to something very vague. Because of this vagueness a new method needs a linkage from the top level to the programs through solid attributes or characteristics. This higher level of fidelity reduces the difficulty of assessing the value of the programs and also provides a more traceable level of detail.

From a corporate view, taking the vision and breaking it down into goals for the various business units is important to keeping all the activities centered on the vision of the organization as a whole. With finite resources, projects which promote the strategic intent of the company should be the first ones to allocate to. Keeping the managers associated with the units in the decision making realm is important to ensure that their firsthand knowledge of operation is utilized in decision making. While the Business Unit vision is defined by the overall organization, the decomposition allows those further down to create vision for their own units.

Government organizations also require a connection of the goals. The size of many government organizations makes the flow of a top level vision down to the individual program offices a difficult process. Having a structured decomposition can bring these needs into forms which can be handled by those individuals making funding decisions. One example of a government agency sequence of levels is the Air Force's Master Capabilities Library (MCL). This document takes high level Air Force capabilities and brings them down to specific threats which programs can address. An example breakdown of the MCL is given in Table 1. The top level (1) describes a vague goal of "Surveillance and Reconnaissance" which is then broken down into its two constituent pieces in 1.1 and 1.2. Each of these pieces is then further decomposed into further detail of what environment each will be applied to. It should be noted that the vague terms are accompanied by definitions which allow the planner utilizing the decomposition to better understand and scope the problem.

Table 1: Example Air Force Master Capabilities Library

1. **Surveillance & Reconnaissance.** The capability to successfully conduct surveillance and reconnaissance missions to satisfy Commanders' Priority Intelligence Requirements (PIRs).

   1.1. **Surveillance.** The capability to systematically and continuously observe aerospace, surface or subsurface areas, places, persons, or things, by visual, aural, electronic, photographic or other means. (Joint Pub 1-02)
      - 1.1.1. Conduct maritime surface/terrestrial surveillance
      - 1.1.2. Conduct maritime subsurface/subterranean surveillance
      - 1.1.3. Conduct air surveillance
      - 1.1.4. Conduct space surveillance
      - 1.1.5. Conduct environmental surveillance
      - 1.1.6. Conduct information surveillance

   1.2. **Reconnaissance.** The capability to conduct transitory missions to obtain by visual observation or other detection methods, specific information about the activities and resources of an adversary or potential adversary, or to secure data concerning the meteorological, hydrographic, or geographic characteristics of a particular area. (AFDD 2-5.2)
      - 1.2.1. Conduct maritime surface/terrestrial Reconnaissance
      - 1.2.2. Conduct maritime subsurface/subterranean Reconnaissance
      - 1.2.3. Conduct air reconnaissance
      - 1.2.4. Conduct space reconnaissance
      - 1.2.5. Conduct environmental reconnaissance
      - 1.2.6. Conduct information reconnaissance

Knowledge Based Resource Allocation

Globalization and the changing technology environment require companies and organizations to allocate resources in an intelligent fashion. Many options and possibilities can present themselves, but it is the choice of the best portfolio which will dictate how much success will be attained. Since the vision of the organization describes the highest level of goals, it follows that the programs which best forward these goals should win the competition for resources.

Traditional resource allocation techniques have failed to meet this correlation between performance and funding. These techniques, identified by Cetron, may seem outrageous but have been shown to be fairly accurate. The "squeaking wheel" involves cutting the funding to every group and then increasing the funding to whoever complains the most or the loudest. “Level funding” is when everyone gets the same funding regardless of past performance or future expectations and is often seen as the “fairest” method. “Past performance” works on the assumption that those who have been successful in the past will continue to be so in the future. “White charger” is giving funding priority to the person or team which gives the best presentation to the decision maker. The “committee approach” is the only one with any kind of rigor and entails a group of people sitting around a table making funding decisions based on how the group decides. In military organization this approach is commonly referred to as BOGSAT or Bunch of Guys Sitting Around a Table. (Cetron 1972)

Benefit to the overall vision is only one aspect of allocating resources to programs. Budget profiles and program interactions are also important pieces of the resource allocation process which should be used for determining which programs to fund. Because an organization has finite resources, it is necessary to maximize the benefit which is obtained for these limited funds. Program interaction deals with whether programs are enablers, incompatible with each other, or offer some sort of synthesis. Incompatible technologies are those which cannot be funded by the organization simultaneously. Enablers are those programs which require others to be funded concurrently in order for research to commence. Synergy between two technologies is when the benefit of both being implemented is greater than or less than the sum of their individual contributions. All these secondary aspects of technology planning are essential qualities of a successful resource allocation.

The New Method: Strategic Planning

Strategic planning is a method for composing a plan which relates the overall vision of a company or organization down to the individual programs and activities necessary to accomplish it. Strategic planning is best defined as looking at where you want to go in the future and putting together the resources, assets, and personnel to get there. What differentiates strategic from other forms of planning is the focus on a broader goal for the future, a vision of what place in the market the company wishes to pursue. The overall purpose of strategic planning is "to determine where your market is going and find a way to continue servicing it (Your 2007 Strategic Plan 2006)." To accomplish this, a strategic plan relates an organization's vision, its overall goals, down to the individual programs, activities, and technologies which will attempt to accomplish the vision. Once these programs are identified, a strategic plan will encompass an overall business plan, or roadmap, which provides a structured timeline for accomplishing these programs as well as the organizational vision.

Strategic planning can be accomplished at any level of an organization, from the CEO or agency director down to the manager overseeing a group of engineers or technologists. Ideally, each level's strategic plan should be interconnected to create a comprehensive plan which relates all the levels of the plan to a central, structured framework. Capturing expertise and knowledge of the individuals involved is essential to ensuring that a plan is solid and robust. In addition to enhancing the quality of the plan, involving a knowledgeable group creates accountability by linking experts with the information fed into the final plan. "Feeling of ownership is crucial if your strategic plan is to remain a useful document" notes Peter Livingston of Stark/Livingston consulting (Molvig 1993). Regardless of which level of the organization is performing the planning there are certain elements which it must possess in order to be successful.

These elements which include the following: long range direction, a framework for linking decisions, being a living document, and being organizationally specific.

Long Range Direction

The most important aspect of strategic planning is the focus on the long term vision of the organization. Vision is the organization's view of where it will be in future in terms of its market, size, and accomplishments. Setting goals and milestones to be reached within a certain timeframe will keep the organization focused on what it wants to accomplish. This long range planning is essential to strategic planning because it sets a target. As Molvig says, "long range planning looks at where you want to be in five years, strategic planning focuses on how to position yourself to get there." (Molvig 1993) In addition to analyzing where the company wishes to be in the future, strategic planning involves determining what outside forces may impact the vision. The actions of competitors, technological breakthroughs on the horizon, and threats from changes in the world environment are just a few of the external forces which should be considered in a good plan.

The future is comprised of uncertainty which complicates any kind of long range planning. Uncertainty is defined by Kirby as "a lack of complete knowledge, or a difference between reality and what is expected." (Kirby 2001) This uncertain future makes the setting of the organization's vision a gamble because the planners do not necessarily know what hurdles they may encounter. To account for this, strategic planning can utilize the concepts of "scenarios" to create smaller, more focused visions based on what possible futures could exist. Drastically increasing gas prices or government reregulation could be some examples of scenarios that would apply to the airline industry. By analyzing what programs or technologies are best for the distinct scenarios, the company will find itself better able to adapt when one of these futures comes into being.

Planning for the future does not imply that every decision can be made in the present. Rather, with a full knowledge of where the organization is headed and what factors will hinder or help the plan, the correct decisions can be made now to get there. “Strategic planning does not attempt to make future decisions. Decisions can only be made in the present. (Steiner 1979)” The goal of strategic planning is to ensure that the organization is in line with where the world is headed. Should that outlook change then it is imperative that the aim of the company change as well. If scenarios occur which have not been properly planned for, then it is necessary for the organization to immediately reassess its plans in light of these changes.

Framework for Linking Decisions

Decisions are made at every level of an organization. From the CEO down to the individual program managers resources are allocated, budgets developed and schedules planned and carried out. Minztberg states, “The assumption of strategic planning seems to be that objectives are decided upon the top management for the entire organization, which in turn evoke the process of formulating strategy.” (Mintzberg, The Fall and Rise of Strategic Planning 1994) Many times, each tier has complete autonomy and little direction provided to link the decisions into a serious, well-conceived plan. Strategic planning provides a framework within which information flow and guidance can be passed not only down to the program managers but also up to the top level decision makers. “Formal strategic planning links three major types of plans: strategic plans, medium range programs and sort range budgets and operating plans (Steiner 1979).” By having a framework available, which necessarily requires information flow, individuals at all levels of the organization will have a better understanding of how they fit into the overall plan.

Living Document

A strategic plan is not a concrete process but, rather, a living document which changes over time. The aims of the organization will most likely remain the same, but the world and market in which it exists will change. A good strategic plan "should be flexible in order to take advantage of knowledge about the changing environment." (Steiner 1979) A plan made one day must be able to change and adapt to a change in the world environment the next day.

Being a "living document" means not only being adaptable but also that the strategy is owned and understood by all levels of the organization. Without good communication Hamel and Prahalad found that "few employees will be able to articulate anything more than the vague ideals or short-term operational goals." (Hamel and Prahalad, Competing for the Future 1994) Strategy only stands a chance of being attained if all levels of the organization understand why they are performing the activities that have been set out for them. Indeed, while direction should flow down the hierarchy, information and knowledge should flow up. The employees closest to the actual actions to be performed are the ones who can give the planners the information they require to form an appropriate plan. This understanding amongst all the levels allows the plan to be owned by the full company and be a living document.

Organizationally Specific

There is no "gold standard" for strategic planning which can handle all of the circumstances surrounding any organization. One of the fallacies associated with strategic planning is that a good plan cannot be developed and implemented by someone outside the organization such as a consultant. A good plan must be put together with the full understanding of those at all levels of the company in order to take advantage of the expertise and advantages and to minimize the weaknesses inherent in any organization. The process for creating the plan must also be accomplished by taking into account the individuality of those involved as well. There is no specific method that works for all organizations; however, it is possible that a generic framework can be created which is adaptable to specific circumstances.

Traits of a Good Strategic Planning Methodology

Putting into practice a methodology which achieves these foundational principles of a good plan requires several traits of the process itself. These can be used as evaluators to determine how much benefit an organization will achieve through the use of one process over another.

Traceability is how visible the thought processes and logic which were used to form a decision are. Due to the impact that resource allocation and strategic planning results have on an organization, there must exist a thorough understanding of not just what decision was reached but, also, *how*. Where did the information come from? What questions were asked? The answers to these questions should be visible to not only the people making the decisions, but also those who are tasked with carrying them out. Linked with traceability is the concept of accountability which deals with knowing who was involved in the process and what contributions they made. This helps in assessing who participated but can also lead to the engagement of the individuals in the organization. Keeping people involved in the process and utilizing their expertise allows for better decisions. It also allows people to feel that they were a part of the plan and to have more of a connection to the outcome than they would had they not been involved.

Longevity is the ability of the methodology to stand up over time and produce a product which is not only applicable at the time that the decision is made but also into the future. This combines traceability and accountability along with the idea that the way in which the programs are ranked and prioritized for planning stands up over time. A strategic plan is not a snapshot in time but, rather, an ever evolving plan which changes as the world environment changes and programs mature. A strong tool is one which can produce a result and then be adaptable to use many of the elements again in a future iteration.

Another trait of a successful methodology is how dynamic it is. In order to make an informed decision it is necessary for the decision maker to be able to make changes in their assumptions and see the results quickly. In addition, to be useful in the initial decision making phase, a dynamic process allows for future users to change the world environment based on their new experiences and see how that might have changed the decision. These tradeoffs allow for trade studies to be performed which a variety of plans for the future.

Having a comprehensive process which takes the decision maker from the problem formulation phase all the way to the execution is important to ensuring that the levels of the organization are appropriately linked and information flows throughout. This comprehensibility is enhanced through the structure and rigor of the process which allows the organization undertaking it to know where they, what they are doing, and what information they need to do it well.

CHAPTER 2

OBSERVATIONS

General Methodologies

Strategic planning has many different identities and based on the source has different properties, outcomes, and processes. These can vary from simply asking questions of management to more specific and ordered processes. While various methodologies have been proposed many deal with different aspects of strategic planning but share many of the same shortcomings.

S.W.O.T.

Nearly all methods of performing strategic planning utilize an examination of the company and the competitive environment. On the specific technique for examining these organization traits is commonly called Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis. This examination is often the first step in formulating a strategy based on a full understanding of capabilities. Strengths are internal traits of the company that refer to the best capabilities of the employees, the areas in which technological advantages over competitors exist, or the areas in which resources are the most concentrated. Weaknesses include areas in which the company is deficient and will either want to improve its capabilities or avoid actions which would require these abilities.

External elements of opportunities and threats are identified in SWOT to determine what the company should attempt to accomplish or avoid. What aspects of the world are particularly conducive to the organizations business and what might hamper it. Opportunities are those events which represent a positive outcome for the company while threats are negative consequences. The planning aspect is addressed by a company conducting a strategy which utilizes the strengths and minimize the weaknesses to capitalize on the opportunities and avoids threats.

Different techniques, ranging from simple to complex, have been proposed to perform the SWOT analysis. Steiner writes that executives can brainstorm and “spend several days identifying what they perceive to be weaknesses, strengths, opportunities, and threats.” (Steiner 1979) In fact, this assessment is sometimes a difficult and vague one. What is strength or a weakness can greatly depend on the context or program in which it is being assessed. Mintzberg asks, “How can we *know* that a strength is a strength without acting in a specific situation to find out.” (Mintzberg, The Rise and Fall of Strategic Planning 1994) In other words, what might be a good quality of the organization in the pursuit of one course of action may be a hindrance for another.

This internal and external analysis, when performed, allows the executive decision maker to formulate the strategy for the organization. SWOT is a processes for asking the questions which allows for information to be identified but lacks a methodology for formulating the strategy aspect. The process allows a company to potentially identify its strength, but it does not create the strategy to use these traits to capitalize on a coming opportunity. Thus, Mintzberg writes that this method of formulating a strategy is “in a sense, biblical: the appearance of grand strategy all at once, fully formed (Mintzberg, The Rise and Fall of Strategic Planning 1994).” This “choosing” of strategy means there is little traceability on how the planning was accomplished and only lists of internal and external issues to provide information in later stages as to why the organization is moving in a certain direction

Balanced Scorecard

In 1996 Kaplan and Norton saw that many businesses were overly stressing the importance of purely financial measurements (Kaplan and Norton 1996). In order to counter this trend they put forth the Balanced Scorecard process which pushes for an organization to take into account non-financial measures such as customer satisfaction, business process efficiency, and learning and growth of the workforce. They said that an organization whose vision is purely based on economics will eventually become stagnant and unable to grow or adapt to changing world circumstances. By successfully balancing all the criteria in these areas a business will not become stuck within a single mindset but will be more efficient and responsive. The overall process is outlined in Figure 1.

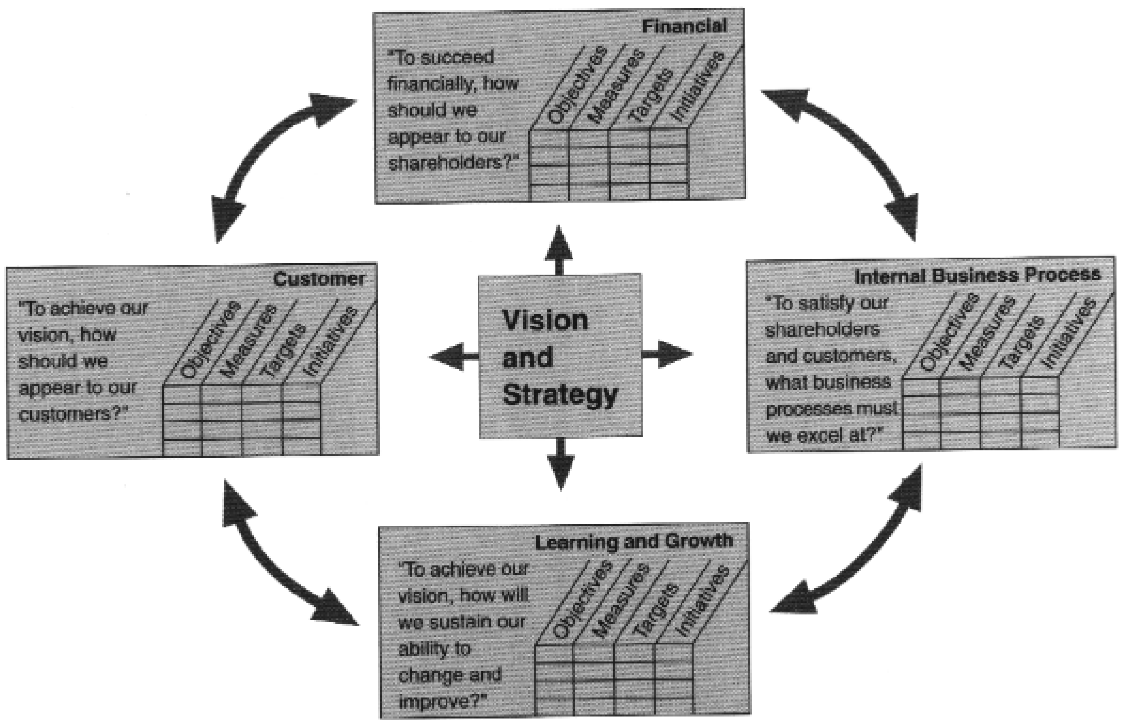


Figure 1: Balanced Scorecard Process Overview

The use of a "balanced" set of goals for a company is intended to keep managers from creating too many workarounds intended only to satisfy a single measurement. For example, in order to satisfy a single goal of on time delivery a manager could create a large warehouse which would fill an order from inventory as soon as it arrived. However, from a balanced standpoint that warehouse could be a financial failure due to the cost of the space and maintaining a broad inventory. It is only by balancing the financial and customer aspects that this would become apparent.

Balanced Scorecard introduces a hierarchy of top level objectives, mid level measures, and bottom level initiatives. Objectives are the goals in each of the four major categories which the organization is aiming to achieve. The degree to which these goals are being met is determined through the measures which are placed on the business metrics in order to compute progress. Targets are defined for each of these measures in order to give the lower level managers and programs near term goals to be achieved. At the bottom of the hierarchy reside the initiatives which are the actual programs and activities which are to be put into practice in order to drive the process along.

The final scorecard produced by this process relates individual actions that the company can work on to “measures”, used to track effectiveness, and finally to the top level goals. While the scorecard is aimed at showing the connection between these levels there is no methodology put forth which allows for the performing of resource allocation or prioritization of activities. Hence, determining which actions are the best for meeting the overall goals is not addressed. (Kaplan and Norton 1996)

Creative Management

One perspective on strategic planning is that the process for creating plans is secondary to the ideas and vision of those in charge. In particular, David Hurst lays out the concept of Creative Management (CM) which tries to address the problem where “the interaction between the mission and the strategy mode is extraordinarily difficult for members within an organization to see. (Hurst, Rush and White 1980)”

What CM seeks to accomplish is the identification of appropriate personality traits necessary at the various stages of the process. In particular, the traits of Sensation, Intuition, Thinking and Feeling are useful for strategic planning exercises. Sensation is the use of the five senses to observe the physical world. Intuition serves as the balancing of the perceptions of the Sensing stage with unconscious patterning processes. Thinking uses logic to connect ideas based on cause and effect. Feeling bases its connections on personal and community values. All these elements are used in different parts of the timeframe which is outlined in Figure 2.

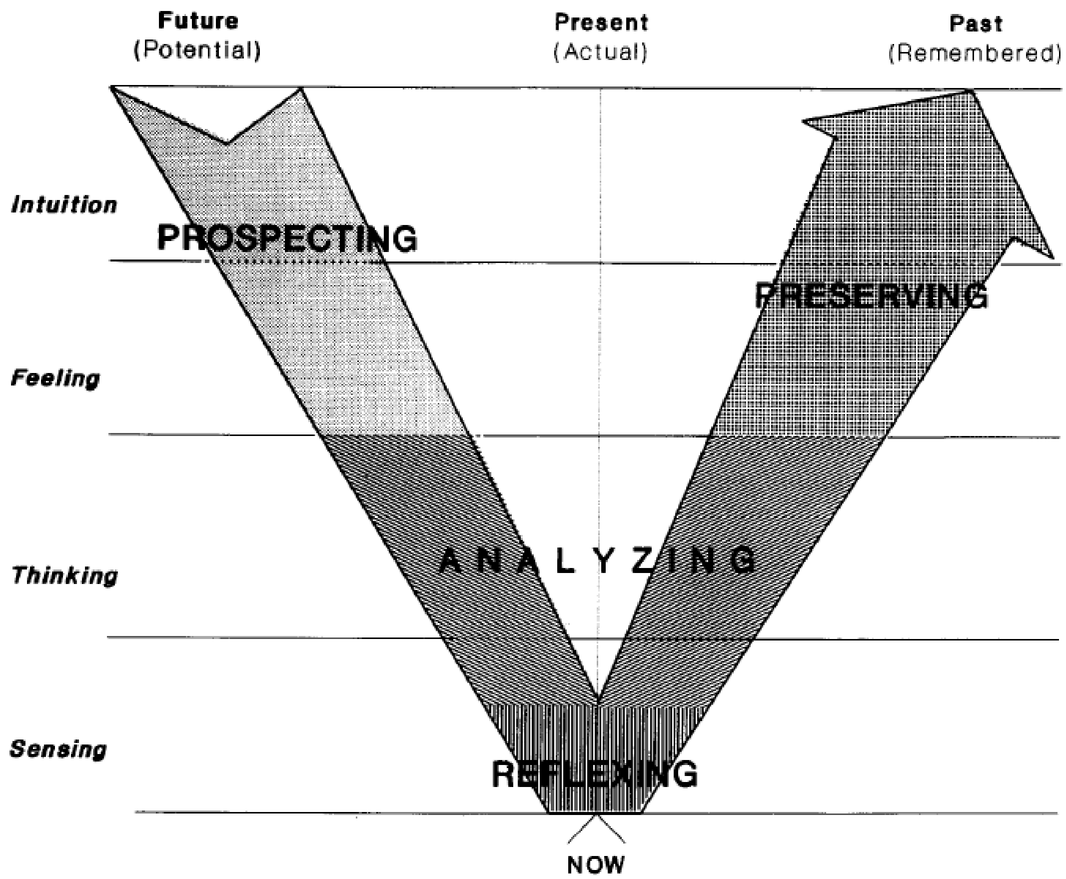


Figure 2: Creative Management Process

In the Prospecting phase, a planner utilizes intuition and feeling to attempt to get an idea about what the future holds for their organization. With this idea in place the analyzing phase utilizes thinking and sensing to understand the particulars of the opportunity availing itself. Sensing is used in the reflexing stage to make the decision needed to capitalize on the opportunity. After a decision has been made another phase of analysis is performed to determine the effects of the decision. Finally, preserving takes the best aspects of the decision made to apply to future decisions.

Creative management has no real formalized process for creating strategy or determining what projects are of most benefit to the organization. The concepts of understanding the past to project success to the future are useful, but the overall process shows such a lack of methodology that not much can be harvested from it. (Hurst, Rush and White 1980)

Quality Function Deployment

Quality Function Deployment (QFD) is a process for decomposing a high level organization vision down to the applicable attributes and programs on which the group can fully act. QFD takes these "What's" of the company down to the "How's" using a series of linked planning matrices. The process has been used extensively in various organizations to link customer requirements to system level attributes. (Air Force Space and Missile Systems 2004)

The "What's" are determined by determining the accomplishments of the organization or product desired by the customer. These customers are not only the people who buy the product but also the other groups which have a stake in the corporate outcome. These can include stockholders for companies or the taxpayers or higher level leadership for government agencies. The components of this vision may start out as things such as "work without breaking," but it is necessary for the company to categorize the results into broad level categories for the purpose of prioritization. Assigning an importance value to each of the top level goals allows the costumer to express what is felt to be the most important ones and allows for a relative rank to be established.

The “HOWs” of the matrix are typically listed across the top of the House of Quality. These elements are engineering characteristics that in a normal QFD exercise are represented by attributes that the product manufacturer feels can be affected by action. Also, the ability to physically measure these attributes which is generally not possible with customer requirements allows the manufacturer to determine if the needed changes are being accomplished. There are 2 “rooms” of the House that are formed by the addition of the “HOWs”. The first is the “roof” which contains the correlation amongst the engineering characteristics showing how much each one affects the others. The second room is the matrix between the “HOWs” and the “WHATs” which shows the relationship between them. This relationship is given a qualitative value of “Low”, “Medium”, or “High” which represents the magnitude of the impact but has no determination of direction.

The qualitative relationships in the main room of the house can be quantified where, typically, a “High” is a 9, a “Medium” a 3, and “Low” is equal to 1. These values are then multiplied by the importance values of the “WHATs” and summed to give the weighted importance of the “HOWs”. Quality Function Deployment has several other calculations that can be factored into the ranking such as risk and the direction of improvements in the “HOWs” being stated but what is illustrated here in Figure 3 is a basic formulation.

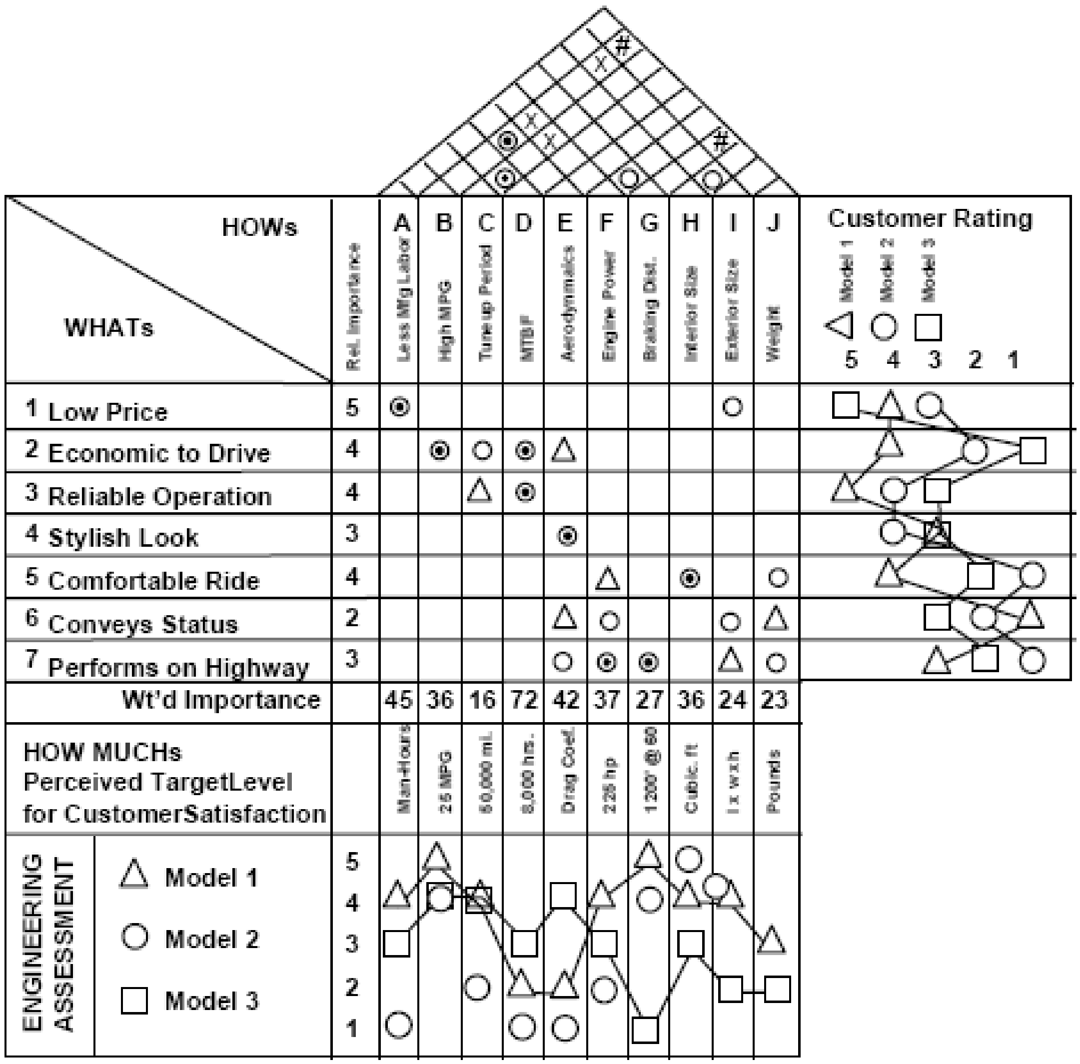


Figure 3: Example House of Quality

QFD includes the term "deployment" because in an ideal application of the process there is more than just a single matrix. From the engineering "HOWs" further levels of decomposition can be created where these characteristics become "WHATs" and a more specific and detailed list of "HOWs" are created. These subsequent matrices provide a depth of study and a linkage amongst several different levels within an organization.

In comparison with other methodologies, QFD provides more comprehensiveness than any of the other methods previously examined. In addition, the structure and rigor associated with this formal process walks the users through the steps needed to form a plan. Some disadvantages exist as QFD does not address procedure for compiling the matrices, which leaves a lacking in the traceability and accountability of the plan. Because the top level requirements are broken down into engineering characteristics the plan created from this methodology can be adapted over time and have a longer lifespan.

Analytic Hierarchical Process

Analytic Hierarchical Process (AHP) was developed by Thomas Saaty in 1971 as a methodology for prioritizing alternatives based on the relative rank amongst them. It has achieved widespread use in the management community and is most commonly used in the software solution *Expert Choice*. The ability to connect various levels of a hierarchy and relate lower level items to higher level ones is one of AHP's most dominant features.

The first step in AHP is to create the hierarchy which will define the levels of the analysis to be performed. Once this has been accomplished pairwise comparisons are made amongst all the alternatives at the same level of the hierarchy for each of the criteria. To do this the decision maker creates a separate matrix for each of the criteria which have the possible alternatives along the top and side. A sample matrix is shown in Figure 4.

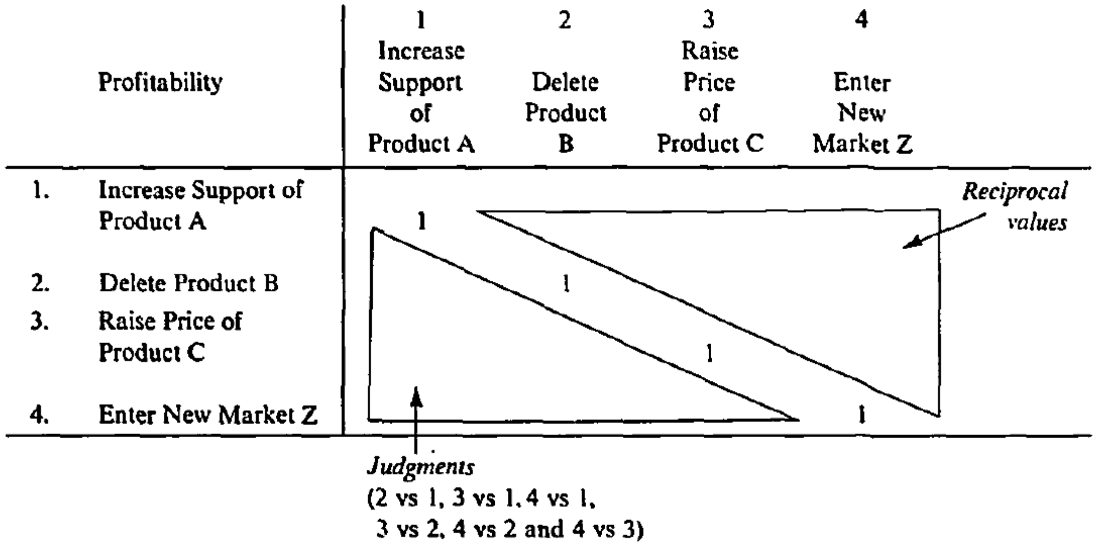


Figure 4: An Example Analytic Hierarchy Process Matrix

The decision maker then fills in the matrix by asking the question: "For this criteria, how much better is the alternative on the left than the alternative above?" In order to quantify the measure of dominance a 1-9 scale is used where the reciprocal would delineate the concept on the left being worse than the one above. The definition of each level of the scale is:

Table 2: Importance Scale for Analytic Hierarchy Process

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two attributes contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance is demonstrated in practice
8	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals of above nonzero	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	

With the matrix completed for each of the criteria the calculations can be performed to elicit the rankings of the alternatives. The eigenvector of each of the criteria matrix is computed which represents the relative importance of each alternative. The impact of the alternatives across all the criteria is determined by weighting the eigenvectors according their importance to the decision maker and summing them. A single value for each alternative is the result and the larger the value the higher the ranking relative to the rest of the field (Wind and Saaty 1980).

AHP is extremely useful in that it provides a distinct ranking amongst the alternatives across many separate criteria. However, the number of judgments required from the decision maker for each level of the hierarchy is $Number\ of\ judgments = C\,\frac{n(n-1)}{2}$ where C is the number of criteria and n is the number of alternatives. From this equation it is seen that for 10 criteria and 40 possible alternatives there would be a required 7800 individual judgments to be made for this level alone. This would tend to be extremely time intensive to be done in a group session as at an average of one judgment every 15 seconds this would take 32.5 hours to complete.

As a drawback, AHP can suffer from rank reversal when inconsistencies occur between the relationships defined by the voters and the final ranking of the alternatives. One method for checking consistency is to determine if the overall ranking of the alternatives matches up with the ranking of the alternatives if they are only considered in pairs. For example, the eigenvalue ranking of three alternatives gives A>B>C and matrices are then compiled of each of the possible combinations in pairs. The eigenvectors of these matrices might result in rankings of A>B, B>C, but C>A which is inconsistent with the original order. This problem is compounded the more alternatives and criteria are evaluated, and a graph of this trend is given in Figure 5 (Triantaphyllou 2001).

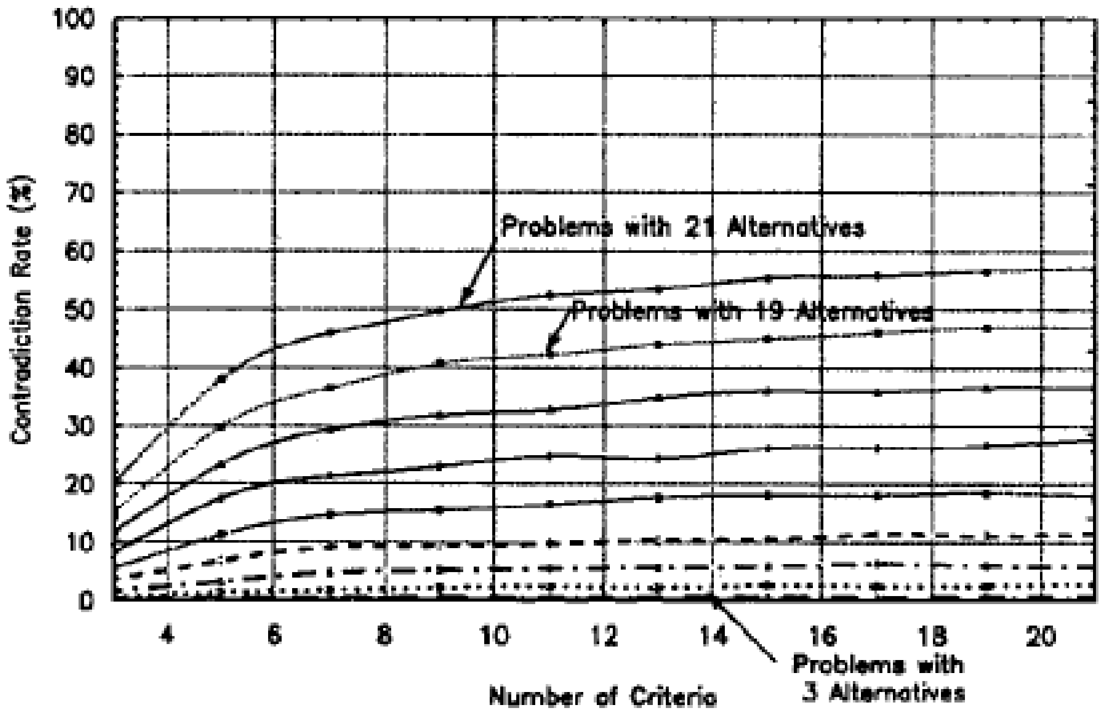


Figure 5: AHP Rank Reversal Trend

Comparison of General Methods

These methodologies for strategic planning lay out steps to analyze when a strategic plan is needed and some of the necessary information to formulate one. Each methodology has its advantages and disadvantages, and in order to assess how well they help an organization to perform strategic planning, it is necessary to compare them. Some criteria will be needed to address the differences and deficiencies of the methodologies. The first point of comparison will be how well each of the processes addresses the various stages of a comprehensive strategic planning framework. The stages include the vision creation, decomposition to appropriate level of fidelity, assessment of program impact, and prioritization of programs. The second group of criteria for assessment will consist of attributes of a solid process such as simplicity, traceability, and adaptability.

Creating a vision to measure the benefit to an organization is an important first step in a strategic planning methodology as it creates a reference to judge programs or technologies. Of the identified methodologies, SWOT provides the greatest impact to this attribute as its selection of questions for identifying the traits of both the organization and external world environment can help the manager to clarify which direction to proceed. None of the other techniques addresses this area and instead tend to take it for granted that it has already been defined.

The linkage of the various levels of fidelity from the vision down to the program level allows the decision maker to identify those areas that will provide the greatest benefit to the organization. Two of these methodologies have hierarchies as one of the central tenets of their design - QFD and AHP. Balanced Scorecard deals with different levels of fidelity by having several levels of design and predefines them as the top level scorecard, measures of effectiveness, and lower level metrics. The focus here is more on how to effectively measure success rather than on what programs should be initiated to achieve said success.

The assessment of program impact is the determination of how the methodology judges a program. QFD utilizes a qualitative descriptor which can later be quantified to assess the impact of a concept to an attribute. Similarly, AHP uses a 1-9 scale to measure relative impacts of one concept over another. Balanced Scorecard does not really have a technique for assessing programs or measures of effectiveness but simply stresses that a broad assortment be included in the analysis. SWOT and Creative Management do not assess programs as well.

Prioritizing the programs allows the decision maker to have a relative ranking of how much benefit is being given the organization by each one. As QFD and AHP were the only two methodologies to assess the impacts of the programs, they will also be the only ones to give a prioritization. When the deployed levels of the decomposition in QFD are condensed to give the impact of the lowest level to the highest, the ranking is purely based on the degree of impact and not the magnitude. This technique works well when prioritizing which engineering characteristics could have the largest impact on the overall customer requirements, as QFD was designed for, but has lacks strategic planning applications. The prioritization of programs by AHP gives a very solid prioritization but does have the issues with rank reversal that were previously discussed.

Simplicity is the measure of the complexity of the process itself. The old adage that “time is money” definitely applies to the corporate management where the more time that is spent on creating a strategic plan, the less time is actually going into running the day to day operations. A process which is simple to implement and utilizes the time of groups of experts only when absolutely needed is essential to keeping the overhead low. Simplicity is not a benefit, however, when the methodology fails to provide many of the primary traits of a good strategic planning methodology. Hence, SWOT, Creative Management, and balanced Scorecard are fairly simple yet ineffective strategic planning methodologies. AHP provides a simple framework, but for large application the number of pairwise comparisons can be extremely large and time consuming. QFD has a similar framework to AHP; but since the assessing of impacts are qualitative and absolute, the number of votes required is considerably fewer.

Traceability is the measure of how well someone would be able to follow the information which went in to the decision making process and determine its origin. Individuals naturally change jobs, and it is necessary for those who follow in their position to understand how the decisions which shaped the organization were formulated. A second piece of traceability is that the visible information should be linked to the people involved to ensure accountability. The plan can only be strengthened if it is known that knowledgeable people were involved in the formulation. Both QFD and AHP are fairly traceable processes as long as they utilize group opinions to create their program assessments. Also, because of the decompositions and levels of both, the final program prioritization can be followed down the hierarchy to determine the strengths of the various relations that contributed to them.

Adaptability is how well the process can be changed for differing circumstances. No two organizations are the same. The level of fidelity available to the projects or organizational needs, the ability to quantify or qualify certain pieces of information, and the number of individuals available for the knowledge gathering are some examples of differences amongst organizations. A good strategic planning process should be able to adapt based on these differences. This is an area where QFD holds a significant advantage over AHP due to the complexity involved with the pairwise comparison matrices. Each new program added would need to be voted against all the others currently included for every attribute. QFD, however, would only require a single new value for each attribute.

Table 3: Strategic Planning Methodology Comparison

Methodology	Vision Creation	Linked Hierarchy	Program Evaluation	Simplicity	Traceability	Adaptability
SWOT	Yes	No	No	Very High	Low	Low
Balanced Scorecard	No	No	No	High	Medium	Low
AHP	No	Yes	Yes	Medium	Medium	Medium
QFD	No	Yes	Yes	High	High	High

Overall Methodology Background

The Aerospace Systems Design Laboratory in the School of Aerospace Engineering at the Georgia Institute of Technology has been at the forefront of systems engineering and aircraft design methodologies for the past decade. In that time a wealth of tools and processes have been developed in order to allow a designer to have more knowledge early and retain freedom later into the design process. These methods gave way to the Technology Identification, Evaluation, and Selection (TIES) Methodology which seeks to use physics based modeling and simulation (M&S) environments to assess the impacts of technology concepts on a future aircraft design. Over the course of several investigations ASDL discovered that it is sometimes not possible for these computer codes to be integrated and implemented in the applicable timeframe for a particular study. In other situations the technology concepts contain so much uncertainty that attributing their impacts to a particular design variable is not possible. In order to account for these deficiencies a broader, qualitative process is needed.

ASDL analyzed the strategic planning problem and adapted the concept of Integrated Product and Process Development (IPPD) to put together a methodology for addressing it. IPPD was identified in 1993 by the National Center for Advanced Technology as the solution to addressing what was viewed as a very rigid technology acquisition process by the Department of Defense which focused only on the performance of a given concept. (National Center for Advanced Technologies 1993) IPPD instead stressed bringing the knowledge and experience from later design elements into the early conceptual decisions in order to properly weigh the costs and risk of a program alongside the performance capabilities.

IPPD is performed in a process, shown in Figure 6, which provides the combination of several different fields into a single environment. Top-down design decision support process forms the basis which is the logical progression of decision making into the progressive steps necessary to being comprehensive. Quality engineering methods focus on probability and harnessing statistics to create a design which is robust to changes and noise. Systems engineering methods provide the components of a functional decomposition to allow for more integrated disciplines and bringing higher fidelity information further up into the decision making process. The following section will outline the generic methodology which is based on IPPD.

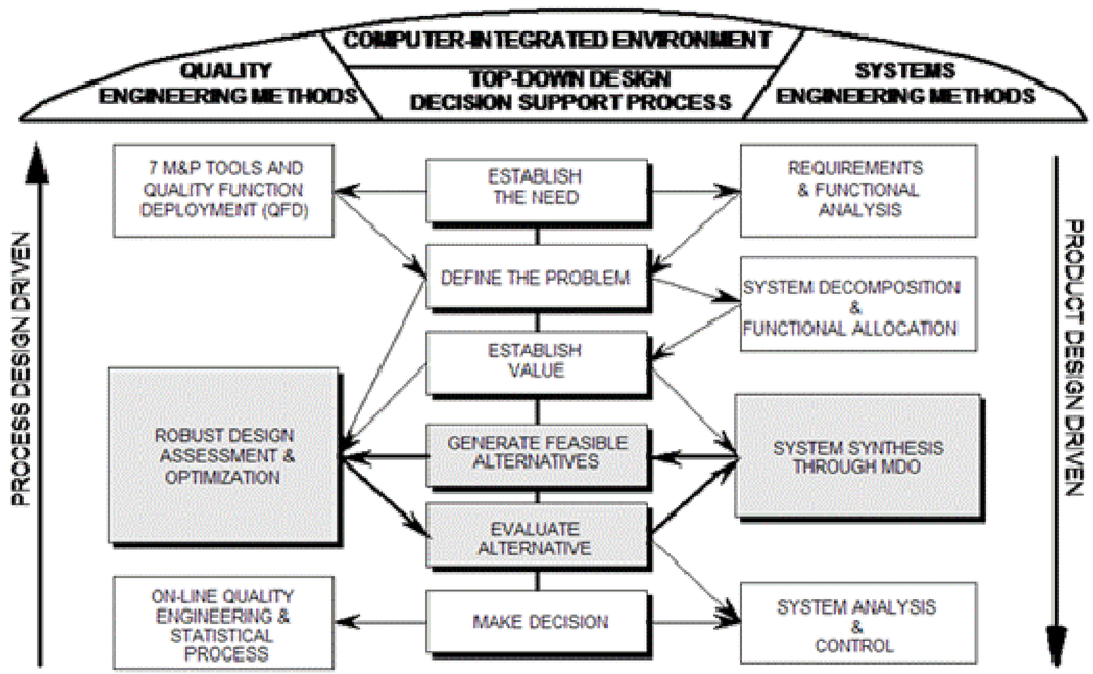


Figure 6: Integrated Product and Process Development Methodology

Define the Problem

The first step in the generic methodology is to define the problem which is attempting to be solved. The importance of laying out a good framework cannot be overstated as there must be a solid base upon which to build the rest of decision making process. From this top-down methodology the starting point for the process is to examine the highest level of the organization at which the decisions are to be made and work down to increasingly more detailed levels of programs.

Organization Vision

Vision is the ultimate aim of an organization as to where it intends to take its business or which capabilities should be examined. At the top level this would be which global markets to pursue or decisions such as whether to increase, keep the same, or reduce market share in a certain area. While the choice of whether to pursue a certain vision is ultimately up to the high level managers, it is essential that the idea is fully formed and attainable. Vision is the highest level goal of the organization upon which the entire strategy will be based, so it must be fully vetted prior to execution.

What has been observed in the process of implementing this Strategic Planning methodology is that many organizations do not have a solid rationale for the formation of their vision. At the highest level of an organization the vision creation tends to take the opinion of a few select managers and uses it to create the roadmap for the entire group. This committee approach is often not supplemented with hard data or analysis and is more opinion based than logic based. At the mid to lower levels of an organization the vision tends to rely on what information and goals are passed down from higher up. Those plans are seen as blessed by the individuals in charge without performing their own analysis to see whether that is the most applicable aim or a secondary aim.

Organization Goals

With the vision established the next step is to determine how to measure the benefit to the organization that programs provide. Goals are top level traits of the vision which are understandable to the higher management levels. These elements should be understandable by those who will eventually make the funding decisions and be ultimate measures of the benefits and costs of a program. Goals should be independent of each other and able to be prioritized according to their impact upon the vision of the organization.

World Scenarios

One of the criticisms of strategic planning is that it is important to create a lasting plan but that it is difficult, and often impossible, to predict how it will ultimately perform.

Mintzberg writes, “Short of being able to control the environment, planning depends on the ability to predict where the environment will be during the execution of the plans.” (Mintzberg, The Rise and Fall of Strategic Planning 1994) Mintzberg also states that planning is the attempt to put stability into the business environment. This stability is fleeting, however, and unable to adapt to the turbulence of the future.

In order to attempt to account for the instability of the future, world scenarios were implemented to capture possible outcomes which could have a positive or negative effect on the organization. Porter describes scenarios as, “discrete, internally consistent views of how the world will look in the future, which can be selected to bound the probable range of outcomes that might feasibly occur.” (M. E. Porter 1980) This “bounding” of the outcomes means that a series of world scenarios should consist of the most probable futures as well as more extreme selections which are less likely but would have a greater impact on the company.

In the terms of an aircraft manufacturer the applicable world scenarios would relate changes in the global market which would affect how a product is perceived by potential customers. A world scenario reflecting a dramatic increase in the price of oil would cause the manufacturer to become more interested in increasing fuel efficiency. This would be a direct impact; but even peripheral effects should be accounted for, such as changes in the demand for airline tickets by passengers.

Problem Decomposition

Attempting to directly link the impacts of programs to the highest level organization goals is a very difficult process. The ambiguity of the top level needs combined with the specificity of the programs means that logically creating a linkage between the two can be difficult. In addition, with less objective rigor in the program impact mapping, it becomes easier for those individuals with a bias or stake in the results to put the best face forward on their programs without also setting out the potential costs.

In order to create a more rigorous and logical connection between the goals and programs the problem should be appropriately decomposed. Dieter identifies two different kinds of decomposition: decomposition in the physical domain and functional decomposition. (Dieter 2000) Decomposition in the physical domain breaks down an overall design into the constituent assemblies and subassemblies required for it to function. This methodology is not as applicable for strategic planning as it requires the planner to already have an idea of the plan which is needed to accomplish the goals. Doing so stifles creativity in the solicitation of concepts and programs which may address the necessary capabilities but are not contained within the physical decomposition of systems.

Functional decomposition identifies “only the subfunctions required to achieve the overall function.” (Dieter 2000) By only including function in the decomposition the nature of the solutions introduced to address them is left unconstrained. The functions are not as evident and easy to describe as the physical domain subassemblies, so there is required a level of brainstorming to determine them. An example of a hierarchy for a naval technology strategic plan is shown in Figure 7.

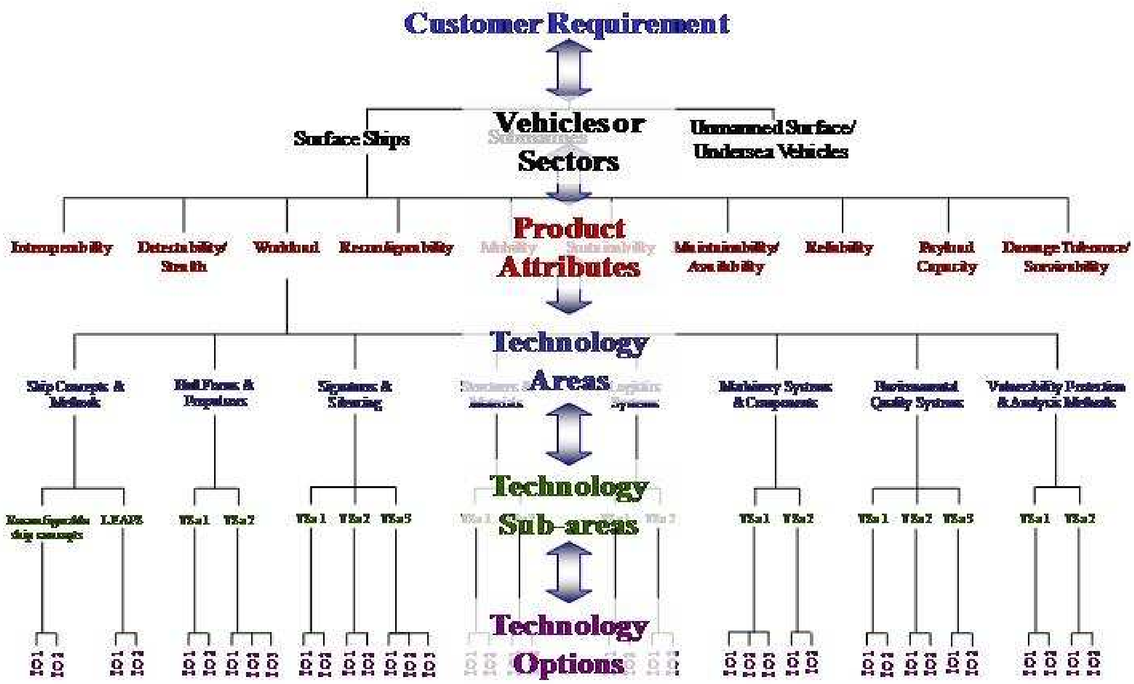


Figure 7: Example Problem Decomposition

In past applications by ASDL, the decomposition of various organizations' visions into their component attributes has been a difficult process. The time devoted to this step has been inadequate, and the results have been more adhoc than reasoned and well thought out. This presents a greater difficulty to the method since all subsequent steps rely on the elements of the decomposition to frame how the programs are generated and evaluated. In addition, the framework has been fixed early in the process but a good functional decomposition should be flexible with time. If a new concept is introduced which incorporates a new subfunction capable of achieving a higher level function, then the hierarchy must be able to adapt and include such an addition.

Gather Information

The second phase of the decision making process is to gather the information necessary to generate and evaluate the concepts proposed to accomplish the vision. This information includes detailed data and descriptions of the proposed programs as well as relationships connecting the various levels of the hierarchy to one another. Both of these classifications of data gathering should be performed in a structured and logical manner in order to ensure traceability of the final plan.

Goal Prioritization for World Scenarios

For each world scenario there exists a vector of values which show the relative importance that the decision makers place on the goals. These vectors allow for the scenarios to be included in the logic of the program prioritization rather than just existing as a thought exercise. In addition to providing a prioritization this examination also allows a confirmation test to be made to ensure that the goals provided represent areas which could be affected by the changing world environment.

In previous applications the methodology for addressing this prioritization as to perform a “chip voting” scheme. This methodology uses poker chips of differing denominations to force voters to show preference to some goals over others. Each individual is given a number of different denominations chips which they then apply to the various goals to indicate their importance. The different amount that each chip is worth eliminates the possibility of people equally distributing importance amongst all possible choices. After all the individuals have voted the information is compiled and an overall group importance vector for the goals to a world scenario is established.

While the chip voting method has been performed with some success there has not been a well documented exploration of other methodologies. Defining the importance for group of goals is a purely relative exercise as the value is determined solely by how much better one goal is than another.

Observation 1: No comprehensive investigation has been performed to determine the best way of creating the prioritization of the goals to the world scenarios.

Research Question 1: How can the prioritization of the goals to the world scenarios be better performed?

Relationships between Levels of the Decomposition

The next step in the creation of the program benefit calculation is the establishment of the qualitative relationships between the levels of the hierarchy. In order to accomplish this, matrices are constructed which relate the elements of each level to the elements of each of the adjoining levels. Each matrix can then be multiplied together to obtain a matrix of relationships between the top level goals and the bottom level programs. An illustration of these matrices is shown in Figure 8.

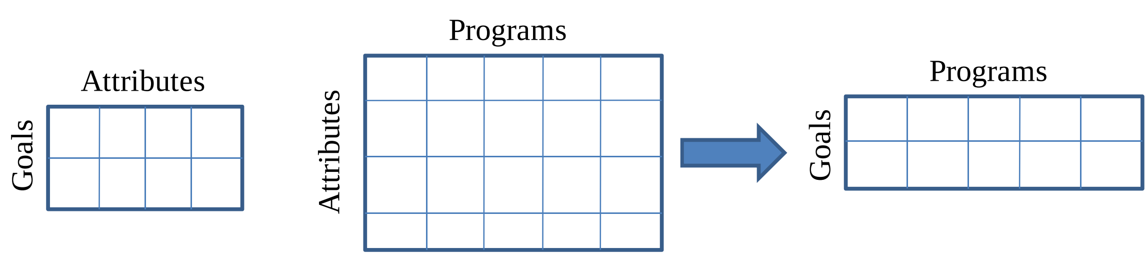


Figure 8: Relating Programs to Top-Level Goals

The values that are included in the relationship calculations are based on a utility function which relates linguistic mappings to a numerical scale. In past applications the mapping scale has been a 7 level scale which is listed in Table 4. Having both positive and negative qualifiers allows the programs to be mapped to not only the benefit which they provide, but also to the costs that are incurred. The numerical scale has varied amongst applications but the values listed in Table 4 are those which are the most commonly utilized. The change in slope of the scale seeks to reduce the impact of the “Weak” measures due to the tendencies of voters to attribute these values to secondary or tertiary relationships. The reduction in the numeric impact of the weak relationships gives the stronger relationships greater relative impact.

Table 4: Program Impact Mapping Scale

Linguistic Scale	Numerical Value
Strong Positive	9
Moderate Positive	5
Weak Positive	1
No Impact	0
Weak Negative	-1
Moderate Negative	-5
Strong Negative	-9

Relationships are obtained by utilizing a group of Subject Matter Experts (SME’s) who are individuals with knowledge and experience in the program areas. There are several different ways to engage the SME’s depending on the organization’s criteria. Some information gathering sessions can be held in person so that a common understanding of the attributes and programs can be assured. If funding is not available to perform a workshop, then online or email questionnaires can offer better solutions. Ultimately, whatever method is chosen, there are several criteria that are needed in order to ensure a reasonable sample of opinion.

First, the participants must have a common understanding of the definitions of the programs and attributes. This is important to ensuring that everyone is voting from a similar knowledge base. Second, the qualifiers of “positive” or “negative” values should be properly designated. It has typically been recommended that “positive” values be attributed to changes in attributes which result in benefit to the organization and “negative” for the direction which are costs. Some examples would be positive for a reduction in the weight of an engine and negative for an increase. In order to enforce consistency the impacts of technologies or programs should be judged based on their impact to the system under the assumption that they have been successfully implemented. Whether or not an expert believes that the program can be launched will be captured in the risk score and other areas of the decision making process and should not influence the relationship vote.

Another aspect of the relationship determination is the use of a common reference point. When evaluating the impact of a technology on an attribute, it is necessary to have a general understanding of the system to which it will be applied. The impact of a new engine fan design will be different for a fighter aircraft or a commercial airliner. If the voters understand the difference and take them into account when formulating their opinion, then the votes will be much more comparable.

After the vote has been taken the deterministic values of the relationships are computed from the results. There are several methodologies which have been used by ASDL in past applications: mean, trimmed mean, and the median. The mean represents the arithmetic average of all the votes of the individuals. The trimmed mean is similar to the mean but excludes a number of points at either ends of the voting distribution. The median is a unique case for the trimmed mean in which all but 1 point is excluded, resulting in the value which has the same number of votes on one side of it as the other. (Hurley and Lior 2002) Each methodology has been used but the median tends to be the most appropriate measure due to its ability to reduce the effects of bias or misunderstanding where a small number of voters place their value at the opposite end of the spectrum from the rest. In such a case a mean would be overly shifted due to the distance from the outlier to the rest of the sample, but the median does not suffer from this complication.

While the median may have been used in the past to determine the will of the group of experts, there still must be an analysis performed on the votes to ensure there are not any great discrepancies. Typically this has been performed by plotting the histogram of the voting distribution and determining if any irregularities are present. However, as the number of relationships grows, the time expense of analyzing all those graphs becomes too great. This leads to an area of improvement in the method to introduce a greater level of statistical understanding which allows for faster and more information analysis of the experts' decisions.

Observation 2: Relationship values should be obtained in such a way as to eliminate statistical bias.

Research Question 2: What voting techniques are appropriate for collecting information from Subject Matter Experts?

Research Question 3: What sample size is appropriate for different voting techniques?

Research Question 4: How should votes be statistically compiled in order to distill the opinion of the group?

Programmatic Data

In addition to capturing the impact of the programs on the goals there also exists other information about the programs which is useful to creating a strategy and portfolio. Organizations have limited resources, such as money, staff, and facilities, and it is important for the decision makers to put together a system of programs which give the most benefit but still fall within those constraints. Gathering this secondary information from those who will implement these ideas is a necessary step to making an informed decision.

Ideally, programmatic information would be stored in a database which is readily accessible to both the planners as well as those responsible for day to day action. As the costs or risks changed over time, this information would be updated in one location which would change all the other places it is utilized immediately. For application to date this has not been available in small part due to the fact that organizations did not fully understand which information they wanted or needed to have gathered. Capturing data remotely from individuals requires the use of a questionnaire or online information elicitation. The aim in such an exercise is to gather as detailed a set of information as possible while taking into account the engagement of those who are providing the data. Utilizing the time of those involved in the programs can cost the organization a great deal of money, so it is imperative that the most efficient process is employed.

Concept Generation

In order to address the vision of the organization the decision maker is required to distinguish between various alternatives. In many cases there does not exist a single alternative which satisfies all the needed goals of an organization. Instead, a portfolio of concepts is required which combines them into a single group. This portfolio may not contain the single "best" program but rather those which give the most benefit for the available cost.

Program Interrelationships

Programs cannot be assumed to be independent of each other. Rather, they can interact for a variety of reasons. There are three major categories of interrelationships: compatibility, enabling, and synergistic. Compatibility is when two or more programs cannot be implemented simultaneously. An example of this would be a resource deficiency such as limited specialized research facilities which can only be utilized on a single program at a time. Enabling relationships are when programs rely on each other to reach certain defined milestones before progress can be made in the others. Synergistic relationships are those where the benefits of two or more programs are different than they would be if only one of them was included. While program interrelationships are physically present in nearly every application to date, their use in the evaluation of alternatives has not been attempted.

Observation 3: Program interrelationships can be present in a portfolio and are not accounted for in the current methodology.

Research Question 5: How can program interrelationships be adequately captured and used to create portfolios?

Concept Evaluation

It is necessary to evaluate the defined portfolios in order to give the decision maker information on which ones are the most applicable for their application. Concept evaluation is dependent on the size of the portfolios as well as the complexity of the program interrelationships and the benefit value function. There are two different methodologies for evaluating a concept, Multi-Objective Decision Making (MODM) and Multi-Attribute Decision Making (MADM). According to Hwang "multiple attribute decision [making] problems involve the selection of the 'best' alternative from a pool of preselected alternatives described in terms of their attributes." An alternative is defined as a characteristic of a concept while an objective has a direction of goodness. (Bandte

2000) Multi-Objective Decision Making techniques "involve the *design* of alternatives which optimize or 'best satisfy' the objectives of the decision-maker." Hence, the difference between the two methodologies is that MADM seeks to evaluate and select current alternatives based on their attributes while MODM aims to optimize a design of a concept in order to achieve optimal benefits. (Bandte 2000) In previous applications ASDL has focused on simply evaluating the current concepts rather than the creation of portfolios and so has utilized purely MADM techniques. Some examples are described in the following sections.

Overall Evaluation Criterion (OEC)

Overall Evaluation Criterion is a technique which assigns a score to an alternative according to the equation:

$$F(x) = \sum_{i=1}^{n} w_i\, f_i(x)$$

Where: w = weight of the criteria

f(x) = value of the criteria for the alternative

This methodology provides a simple process for computing a score for each alternative in order to assign a corresponding ranking. The simplicity of the OEC formulation also presents some drawbacks to the methodology. Because of the simple addition calculation of the OEC, alternatives which score well on the highest rated criteria while being very poor in other areas can dominate. Others which score less on the most important criteria but are beneficial to all can be seen as inferior when in actuality they are the more preferable solutions. In addition, without a normalization of the values, comparison amongst alternatives affecting different criteria will be deficient.

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) utilizes the Euclidean distance between each alternative and an "ideal" positive and negative alternative to compute a score. The "best" alternative has the smallest distance to the positive ideal solution and the longest from the negative ideal solution. The matrix of values is shown here:

	Alternative 1	**Alternative 2**	**Alternative 3**	**Alternative M**
Criterion 1	x_{11}	x_{21}	x_{31}	x_{M1}
Criterion 2	x_{12}	x_{22}	x_{32}	x_{M2}
Criterion 3	x_{13}	x_{23}	x_{33}	x_{M3}
Criterion N	x_{1N}	x_{2N}	x_{3N}	x_{MN}

The first step is to normalize the values in order to allow a common comparison across all the criteria. This is accomplished by dividing each value by the sum of squares of all the alternative values across all the alternatives according to the equation:

$$\boldsymbol{r_{ji}} = \frac{\boldsymbol{x_{ji}}}{\sqrt{\sum_{j=1}^{M} \boldsymbol{x_{ji}^2}}} \qquad \textbf{(1)}$$

The positive ideal is calculated for each criterion as the best value amongst all the alternatives and normalized according to the equation

$$\boldsymbol{r_i^*} = \frac{\boldsymbol{x_i^*}}{\sqrt{\sum_{j=1}^{M} \boldsymbol{x_{ji}^2}}} \qquad \textbf{(2)}$$

Where x_i^* is the maximum value for criteria i across all alternatives.

The negative ideal is calculated for each criterion as the as the worst value amongst all the alternatives and normalized according to:

$$\boldsymbol{r_i^-} = \frac{\boldsymbol{x_i^-}}{\sqrt{\sum_{j=1}^{M} \boldsymbol{x_{ji}^2}}} \qquad \textbf{(3)}$$

Where x_i^* is the minimum value for criteria i across all alternatives.

The Euclidean linear distance from the positive ideal solution (S_{j*}) and the linear distance from the negative ideal solution (S_{j-}) are then computed according to:

$$S_{j*} = \sqrt{\sum_{i=1}^{N}\left(w_i r_{ji} - w_i r_i^*\right)^2} \tag{4}$$

$$S_{j-} = \sqrt{\sum_{i=1}^{N}\left(w_i r_{ji} - w_i r_i^-\right)^2} \tag{5}$$

The final scores of the alternatives can then be computed using:

$$\boldsymbol{C_j} = \frac{s_{j-}}{s_{j*} - s_{j-}} \tag{6}$$

Using TOPSIS eliminated the problem of several good criteria for an alternative dominating the remainders which was present in the OEC. In this case if the alternative has the best value for several criteria and the worst for all the others, that will be readily apparent and handled by decreasing its distance to the negative ideal solution and conversely its rank. (Bandte 2000)

Decision Support System

After a benefit score has been given to each of the alternatives, the information is compiled into a visualization system to allow the decision maker easy access. This is done in what is called a Decision Support System (DSS) which Bhargava says "are software products that help users apply analytical and scientific methods to decision making." (Bhargava, Sridhar and Herrick March 1999) DSS's found an increased use and development in the 1970's and 1980's with the rise in popularity of the desktop computer. With easy access to computing resources these frameworks allowed for large data sets to be expressed in manageable formats which managers could more easily understand. For the ASDL formulation the DSS is implemented in a Microsoft Excel® framework. The ranking of programs are given along with cost and schedule information. Dynamic sliders are also included on the weights of the top level needs in order to allow the decision maker to adjust the values and see the impact on the ranking of the programs.

Observation 4: Organizations have a variety of types of information which can be used to make decisions, and any methodology must be able to address multiple criteria in a single methodology.

Research Question 6: How should the performance data be put in front of the decision maker in order to give them information that will be the most useful?

Summary

Several strategic planning and resource allocation methodologies exist which address some of the overall problem. However, they lack comprehensiveness and the abilities to be traceable, adaptable, and simple. The generic process adapted from Integrated Product and Process Development provides much of the needed capabilities but lacks sufficient research and rigor in some areas. The lack of a strong methodology for eliciting the opinion of subject matter experts, the inability to determine the bias of the voters, and statistical deficiencies of the sample are of particular concern. In addition, the complete inability to handle technology interrelationships leaves the current methodology unable to handle many classes of applications to which it might otherwise be useful. Addressing these issues will provide a stronger methodology for aiding the decision maker in creating an overall business plan.

CHAPTER 3

BACKGROUND

With the gaps identified and Research Questions formed, a literature analysis was performed aimed at identifying methods which would be compatible with the issues raised. Some of these techniques come from other fields and can be applied to this application, and others are new solutions. The walkthrough of these ideas will follow the same decision making process flow that was identified in the previous chapter and is shown in Figure 9.

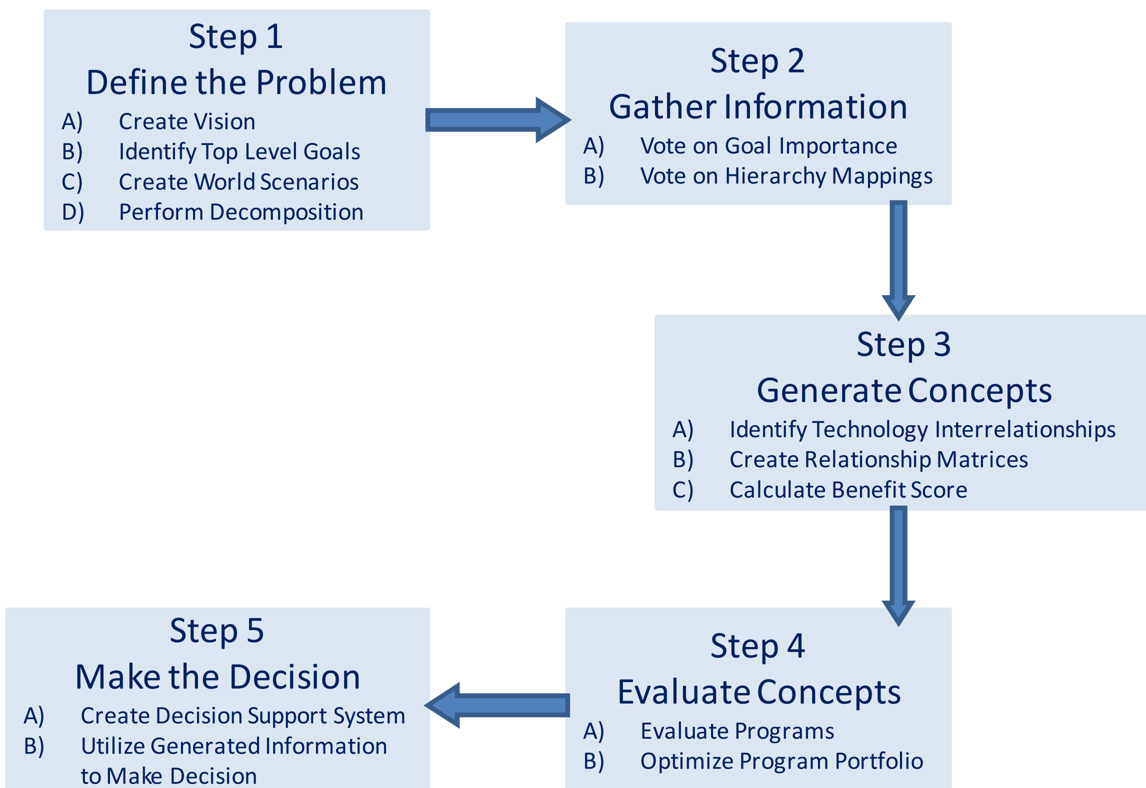


Figure 9: Strategic Planning Framework

Step 1: Define the Problem

The deficiencies of this area stemmed from a lack of understanding in the formulation of the organization vision and hierarchy of attributes. Since defining the problem is the foundation upon which the plan is built, it is essential to making sure it is solid and well thought out.

Vision is defined differently depending on which level of the organization the plan is being formulated. If the Strategic Plan is being created at the top level of the organization, then the vision will come from the CEO or the upper management. If, however, the planning exercise is at a more focused level such as a business unit or focus area, then the vision may be a more specific idea or one which has been filtered down from the higher level management itself.

Identifying the elements of the vision which can be used for decision making is an important stage of the process and one which has not been adequately handled in the past. Several elements of the systems engineering process are applicable and useful for this phase of the methodology. The Seven Management and Planning Tools are a set of Total Quality Management techniques which can be utilized to express a vague concept as its constituent pieces.

The first tool, affinity diagrams, are used to categorize ideas and thoughts during brainstorming sessions. This tool begins by writing the ideas on note cards or sticky notes. Then, the note cards are sorted into the groups and given “header names” which represent the ideas contained within. This method allows for brainstorming to be performed in a logical and structured way; many diverse ideas presented can then be organized into manageable pieces. Done in a group setting, this methodology lends itself well to allowing all the individuals to express their ideas and opinion and then collect all the information. Utilizing the knowledge and experience of all those involved allows for a substantial traceability and accountability for the overall plan. In addition, allowing for the definitions of the items to be a result of the group consensus means that a clear understanding is developed amongst the participants. An example affinity diagram is given in Figure 10. (Kelley 2000)

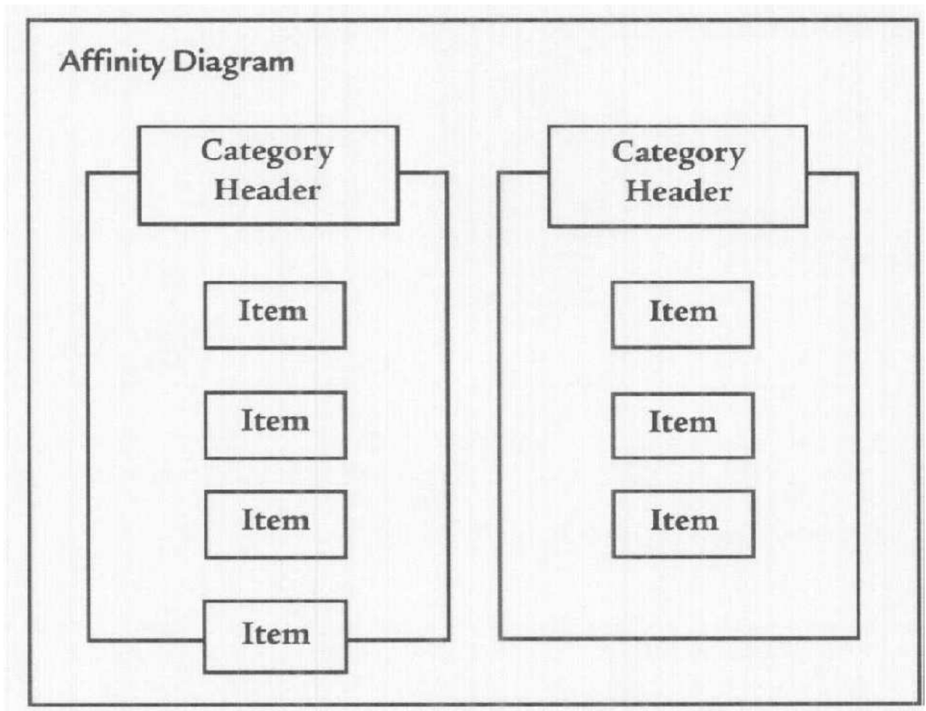


Figure 10: Affinity Diagram (Kelley 2000)

Interrelationship digraphs are the visual representations of the connections between the categories of ideas identified by the affinity diagrams. By mapping out not only where relationships exists but also in which direction they go, it is possible to identify drivers and supporting concepts. (Sandras 1996) This further classification allows the organization to better decompose the hierarchy of needs and objectives which will accomplish the vision by identifying the key drivers. In addition to identifying important relationships, gaps can also be determined based on important concepts which have no direct linkages form other categories. An interrelationship digraph is illustrated in Figure 11.

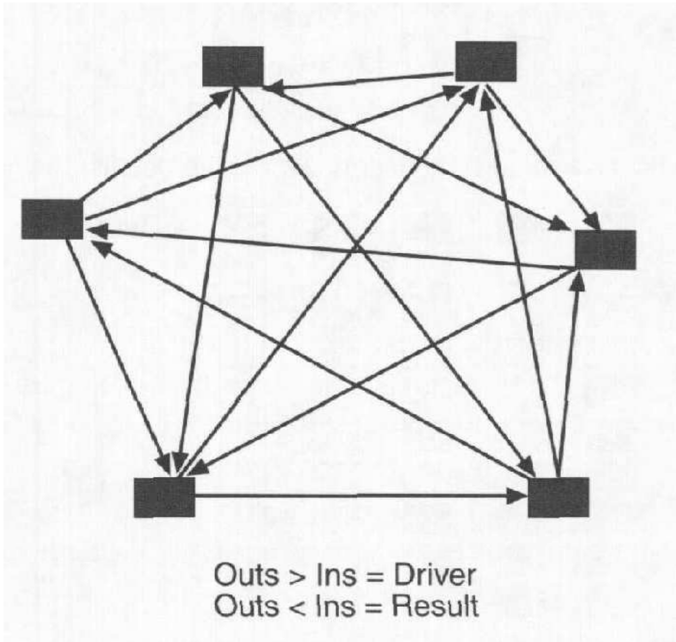


Figure 11: Interrelationship Digraph

The next step in decomposing the vision is the creation of tree diagrams. This exercise takes the identified drives from the interrelationship digraphs and affinity diagrams and decomposes it to actionable items which the organization can affect. (Sandras 1996) Decomposition is performed again as a group exercise with individuals in the group identifying sub components of each of the drivers to create a family tree. Iteration and use of affinity diagrams and interrelationship digraphs should be used for any tree elements which still retain vagueness. Indeed, performing relationship analysis is an important step to creating levels of the hierarchy that minimize the interrelationships of the elements at that level.

These management and planning techniques allow the vague ideas of the organization vision to be broken down in to the core pieces. These pieces are then reconstituted in a structured and logical manner to form a well decomposed and ordered view of the vision. This problem definition can then be utilized in the later stages of the process where information can be used to create the relationships between the levels of the decomposition and allow the decision maker to make a logically sounds and well informed final determination.

Step 2: Gather Information

With the hierarchy of the problem appropriately decomposed into actionable elements linked to the highest level goals, it is necessary to gather information as to the impact of the relationships between the various levels. This action is best performed through the use of numerical data from experimentation or modeling and simulation. However, in their absence the knowledge of Subject Matter Experts (SME's) can be appropriately substituted. There are two different kinds of expert elicitations which are performed in the course of the strategic planning and resource allocation process. The first is for Prioritization Matrices which represent the importance values of organization drivers. The second are Relationship Matrices that give the mapping between the actionable items in different levels of the decomposition hierarchy.

Prioritization Matrices

Prioritization matrices are an element of the Seven Management and Planning Tools which allow for organizations to define the priorities and help to eliminate the use of "pet projects". It is recommended to utilize these matrices in the presences of "what if" scenarios. (Sandras 1996) Scenarios will allow for different matrices to be constructed based on a set of potential outcomes. Each matrix is set for a different world scenario, and the decision maker can switch the active matrix based on what they feel is the most probable or most important scenario. For this formulation these scenarios come in the form of the world environment and possible future outcomes which affect the organization goals. How the matrix is constructed is an important area of research.

Importance is a very human concept which relates the magnitude of the impact that an action or trait will have on success or failure. Because it is subjective, it varies from individual to individual and does not have an ideal "true" value. Therefore, it is very important that when acting upon priority information that these importances are well established and in line with the thinking of the people involved in the organization. Utilizing group voting to combine the collective opinions of several different people can allow for more robust prioritizations for the organization.

Research Question 1: How can the prioritization of the goals to the world scenarios be performed better?

Preference for which goal is more important for a particular world scenario can differ amongst a group of people. In order to account for these differing opinions and create a robust solution, prioritization should be performed in a group situation. This aggregation of the opinions of a large sample of planners and decision makers ensures that the final solution is independent of the individual concerns of any one member. How the voters perform this task and how the information is collected are crucial areas to examine.

<u>Rank Ordering</u>

The first method for establishing priorities of the attributes is to have the voters in the group place all the goals in order from most important to least. A score can then be given to each goal based on the ranking given to it. One such scoring methodology is the Borda Rule which for m alternatives assigns a score of m-1 for first place, m-2 for second, etc. (Fishburn and Gehrlein Winter 1976) Compiling the votes of the entire group is then accomplished once the scores have been assigned to the goals. The values can be summed across all voters and normalized to give a ranked listing with corresponding importance values. The total point scores can be used to assign the weights to the goals for the world scenario in question. There are several advantages to this method with the first being the ease of implementation. Asking for a group of people to simply rank order a list of goals with respect to a world scenario can be accomplished in a short timeframe. Secondly, the order of the goals importance would be very traceable back to the rank orders that were assigned by the voters.

The major disadvantage to this method is that with the voters simply laying out the order of priority and not the degree then the final weights may not be true representations of the importance that the voters feel. For instance, 3 goals exist (A, B and C) and the voters feel that goal A is three times as important as goal B which is twice as important as C. This greater level of importance could not be captured by having the voters simply express the order of importance in a ranking scale. The simplicity leads to a lack of fidelity in the final importance values.

Pairwise Comparison

The second method for creating the attribute importance ratings based on the world scenarios is the pairwise comparison technique. As part of the previously mentioned AHP, this method requires the voters to compare the goals against each other and determine not only which of the two is the most important but also by how much. This type of analysis results in a ratio scale assessment which offers more granularity into the ranking of the goal. (Berander and Jonsson 2006) The advantages of this methodology is that it is extremely simple to implement and for the voters to form their opinions. The disadvantage is that with large numbers of goals or world scenarios the number of votes required from the planners can become large. This problem is compounded at this level of the analysis due to the high management level associated with these voters. The higher the position, the more the time of these individuals costs.

Cumulative Voting

Cumulative voting (CV) is a method that allows the users to distribute points amongst the alternatives. It has been used successfully for several years in political elections and business decisions such as electing members of a board of directors. The points can be allocated in any amount, and the voters are allowed to spread them however they see fit. The vote totals amongst the population are then summed to give the overall group decision of the importance rankings. Such a system is extremely simple but still allows for a great deal of fidelity to be expressed in the goal importance.

Initially this concept was used to combat the practice of gerrymandering of election districts. In the past, cities or counties were divided into voting districts such that one group would represent a slight majority in many smaller election areas. Thus when each one voted to select a single member to represent them, the larger majority would win in every district and ultimately have complete control over the entire ruling board even though statistically they only represented slightly more people than the opposing party. Cumulative voting, however, was used to do away with the smaller election districts and have the vote be city or county wide with each person having a number of votes equal to the number of positions available on the board. The people with the largest number of votes at the end win positions on the board. What results is that if the minority places all their votes on a single person or divides them amongst 2 or 3 people then they are ensured at least one place on the board. Thus the actual breakdown of the county is better represented in the elected office. (Lockard 2006)

One disadvantage to this methodology is that it can be difficult for a voter to determine exactly how to distribute the points. The two most common ways are to evenly spread the points amongst the alternatives which are viewed as important or to give all the points to a single alternative. (Berander and Jonsson 2006) To minimize this issue a form of CV was created that breaks up the possible points allocated to the voters into different denominations which cannot be broken up any further. For example, 100 points may be allocated as two 20 point tokens, three 10 point tokens, and six 5 point tokens. This allows the individual to allocate as they see fit but makes the determination of values much easier. The disadvantage of such an adaptation is that only values which represent a possible combination of the tokens are possible. If the voters feel that another value is more appropriate, then it is not possible for that to be expressed in this formulation.

Benchmarking

For the purpose of determining which methodology to utilize in this formulation, it is important to look at the advantages and disadvantages and how they relate to the problem at hand. Since these priority values will later be used as weights on terms within an equation, it is important that more granularity than just the rank of the goals be provided. For this reason the use of the Rank Order scheme is rejected. The remaining two methodologies both provide not just a rank but a quantitative descriptor of the differences between the priorities of the goals. Determining the best choice amongst these methods requires a look at the traceability of the results. With the pairwise comparison, the motivation behind the votes can be broken down to a level where an interested party could see how each voter gave a value of how much more important one goal was than another. The furthest level of accountability present in the cumulative voting method is the values assigned to each of the goals. The number of voters and the cost of eliciting opinion must be taken into account as well. For large problems with a large number of top level goals or world scenarios then the cumulative voting technique would show preference over the pairwise comparison. For smaller applications this selection would be reversed.

Table 5: Comparison of Prioritization Matrix Voting Techniques

Methodology	Fidelity	Simplicity	Adaptability
Rank Order	Low	High	High
Pairwise Comparison	High	Medium	Medium
Cumulative Voting	High	Medium	Low

Relationship Matrices

The relationship matrices are used to represent the impacts of the elements in each level of the hierarchy to the adjacent levels. A representation of this is shown in Figure 12. Relationship matrices are at the heart of the QFD methodology previously discussed, but this new process requires some modifications to the existing framework. Obtaining the values for this matrix from the Subject Matter Experts is done through group voting much like that previously discussed with prioritization matrices. However, several differences between the two applications make necessary the use of different techniques. First, the concept of prioritization is a purely relative one with no absolute value being given to the goals but merely how they relate to one another. In the formulation of the relationship matrices the different levels of the hierarchy are being mapped and the strength of the impact addressed not the relative impact of all the elements at the same level. Second, there is the potential for a much larger number of votes than there was for the prioritization matrices. This is due to the decomposition creating many levels of relationships which will need to be defined; a problem which is only compounded by large numbers of programs which may be proposed.

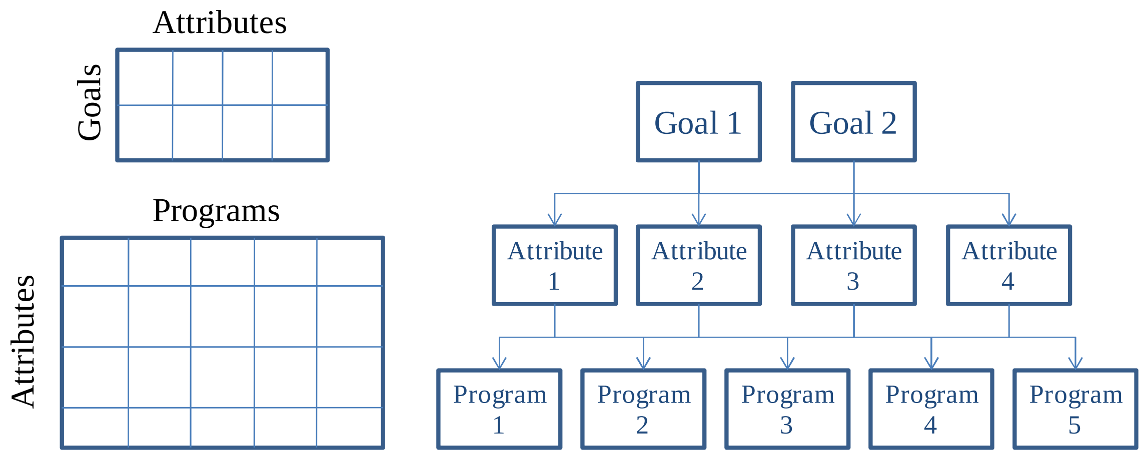


Figure 12: Relationship Matrices

Research Question 2: What voting techniques are applicable to obtaining the relationship values?

There are several different techniques for capturing the will of the group in a voting environment. These methods relate how the people involved in the information elicitation are brought together and their opinions compiled. The selection of possible formulation for an application will be based on the dynamics and resource availability of the organization creating the strategy.

Delphi Technique

The Delphi Technique was developed by the RAND Corporation to perform technological forecasting. (Tersine and Riggs 1976) The idea was that a group of experts could be more accurate than any of them individually. In order to remove bias from the group, the participants are not given any knowledge of who else is participating and, thus, there are no in-person group discussions. Instead, information is passed through a third party in the form of questionnaires which also has the added benefit of not requiring the participants to be in geographical proximity with each other.

The process for following the Delphi technique is shown in Figure 13. The first few steps deal with scoping the problem to be addressed and compiling the correct group of people that will be used to answer the question. Once this is completed then the first questionnaire is sent out to the group members. They answer the question and state the reasoning and assumptions that were made to come to that conclusion. This is then returned to the information compiler who processes the results and puts together the sampling of the votes. If the statistical distribution meets a pre-specified value for consensus, then the procedure is complete. However, if no consensus is reached then another questionnaire is dispatched which not only includes the question but also the statistics of the group and the reasons provided by the experts. The compromise that comes from Delphi is that given this new information that only one expert may have thought about, the group as a whole can refine their votes and come to a common understanding of an answer to the question. Once consensus is reached, then the final results are collected and put into a final report.

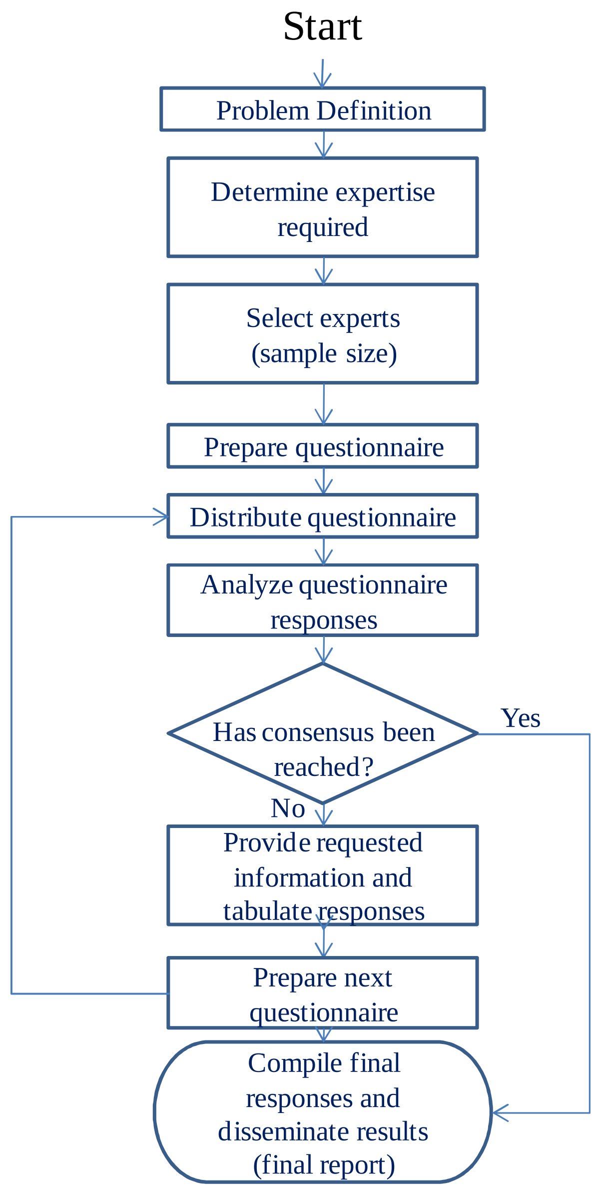


Figure 13: Delphi Technique Procedure

One advantage to the Delphi Technique is that the resulting consensus opinion of the group is something that was arrived upon by all or the majority of the members. In addition, the requirement to collect the reasoning for the decision of each voter provides a great amount of insight and traceability for the process by allowing planners to understand not only what consensus was reached but also what information framed that opinion.

Typically, it has been found that 3-4 iterations with questionnaires are needed to come to a compromise amongst a group of 10-15 experts. While this methodology would work well for a single question or several closely related questions, the time involved in relating a large series of programs or technologies could become problematic. Also, this time element can tend to cause people to come to a forced group consensus simply to be done with the exercise. Since they have full knowledge of the distribution of the rest of the votes, they can tell if their vote represents an outlier and change their opinion simply to complete the exercise sooner. (Tersine and Riggs 1976)

Nominal Group Technique

The second methodology utilizes a very simple technique in order to capture the relationships from a group of voters. Called the Nominal Group Technique, this method brings the voters together in a workshop where the votes are taken. Here the voters can be briefed as a group on the definitions of the attributes and descriptions of the programs. Using the same information for reference ensures that while the voters have different knowledge and experiences which influences their vote, they are all using a common set of information (Roth, Schliefer and Switzer 1995)

Bias can be present when members of the group fall back on simplistic thinking instead of making a knowledgeable, well informed decision. Groupthink is one such bias in which members of the group are more concerned with coming to a consensus than in creating a well reasoned decision. A facilitator can reduce the more extreme versions of bias by relying on a secret ballot where a voter will not know the decisions of the other members of the group. In addition, restricting the discussion of the programs and attributes to relevant topics and purely informational purposes can restrict dominant members from imposing their will upon the others. (Jones and Roelofsma 2000)

There are several advantages to using this methodology within the framework of a strategic planning and resource allocation application. The first is that there exists a great degree of traceability to the final decision since the voters are all briefed as a group. Erroneous or incorrect relationships can be traced back to the information provided as well as items which were brought forward in the discussion process. The disadvantages stem from the difficulty in getting a good sample of SME's together in a workshop. For a large number of relationships the number of briefings and votes can becomes large enough to create problems in keeping people's attention. In addition, the costs for getting people together in a single location can become burdensome.

Online Questionnaire

This method is an attempt to eliminate the organization resource limitations which are present with Nominal Group Technique. In this case the definitions of the attributes and the descriptions of the programs are provided to the voters in an online format, and they are allowed to fill out a questionnaire in their own time. While there still exists a significant amount of time that they must devote to the exercise, it can be broken up over the course of several days or weeks and done in much smaller pieces than the workshop allows. In addition, the need for expensive travel is eliminated.

A unique advantage to a web based application is that the content of the voting can be dynamic and change based on the views of the individual voters. In one such questionnaire a question about whether a technology had any applicability to a group of attributes could be followed up with specific relationships questions if the answer was in the affirmative. However, if no such applicability exists then that realm of questioning could be excluded. This would allow for a greater fidelity to the data without requiring the voters to answer every single question at all the levels. (Hadre, Xie and Ly 2005)

The disadvantage to this methodology is the elimination of briefings and discussion on the program and attributes. Without this discussion the group members could be utilizing different information to frame their decisions, and if a question arises as to the scope of a project, it can take several days for the question to be emailed to the appropriate party and an answer to be distributed to all the participants. In this case it is extremely important that only extremely high quality information is distributed to the voters in order to minimize the questions which may arise.

Benchmarking

The choice of which of these techniques to employ should be based on the scope of the relationships being addressed and the resources available to perform the information gathering. A small set of relationships would be best suited for using the Delphi technique based on its focus on not just the magnitude of the impact but also the reasons from each of the Subject Matter Experts. For larger sets of relationships to be gathered the decision of utilizing the Nominal Group Technique or a web based application is most suited to how much time and funding is available to get the participants together. NGT is ideal for when gathering people is not problematic or if there is not much time available in a short schedule application. An online questionnaire takes longer calendar wise, but the time can be broken up by the participants in order to not spend a bulk of several days in a workshop. Ultimately this decision is up to the organization.

Table 6: Relationship Matrix Voting Techniques Comparison

Methodology	Fidelity of Answer	Individual Flexibility Allowed	Time Required
Delphi Technique	High	Medium	High
Nominal Group Technique	High	Low	Low
Online Questionnaire	Medium	High	Medium

Research Question 3: What sample size is appropriate for different voting techniques?

<u>Voting Sample Sizes</u>

In compiling the opinion of Subject Matter Experts, it is necessary to understand how many people should be involved in the voting process in order to determine a sample size. The field of statistical sampling and surveying has long studied how many people are needed in order to reduce the margin of area of the sampling group from that of the overall population. In addition to these statistical factors, it is also necessary to take into account other considerations such as cost and time when determining the size of the sample which should be involved in the decision making.

Sampling theory is the field of determining the characteristics or traits of a population by examining the characteristics or traits of a smaller group. The goal is to determine how large the smaller group should be in order to give an acceptable margin of error for the final statistics. The use of this methodology for determining how many people to include in a group opinion poll of subject matter experts is difficult. The most problematic piece is that it is difficult or even impossible to determine the sample size of the overall group that is being studied. For a national Presidential election poll the population size would be the number of registered voters across the country which is a number that could be determined by a pollster. However, for the determination of how a program would affect the attributes of a system, this population size is not a readily available figure. Indeed the nature of the question is such that no true answer exists. (Bartlett, Kotrlik and Higgins 2001)

While finding the representative sample of a larger population may not be possible, a sample size can be estimated based on the acceptable error. The two types of error which are necessary to understand are the margin of error and the Type I error or alpha level. The margin of error is the difference between the "true" mean of a distribution and the "sample" mean. The alpha level is the probability that the true margin of error exceeds the acceptable margin of error.

Once these values are appropriately determined calculating the survey sample size required can be accomplished utilizing the following equation:

$$n_0 = \frac{(t^2)(s^2)}{d^2} \tag{7}$$

Where:

t = value level for the selected alpha level

s = estimate of the standard deviation

d = acceptable margin of error

The process for determining the size appropriate to a certain problem is to utilize the above equation to calculate a sample number of voters. This formulation requires an estimate of the standard deviation which is based on the scale of the voting being performed. Once the voting procedure has been performed then the true standard deviation of the distribution can be computed and used in the equation to determine whether the sample was sufficient or whether more votes are needed in order to satisfy the specified conditions. It is then at the discretion of the planners whether to revote the same SME's with further discussion or to solicit the additional opinions of individuals who were not present in the first session. (Bartlett, Kotrlik and Higgins 2001)

Research Question 4: How should votes be statistically compiled in order to distill the opinion of the group?

Capturing the will of the voters is an important and necessary step to creating the relationship matrices. How the individual opinions of the members of the group are collected can change the ultimate value of the impact. In addition to pulling out a single value for the vote results, it is also necessary to statistically examine the vote distribution in order to ensure that there are no discrepancies which could have resulted from misunderstandings amongst the voters.

<u>Vote Distribution Statistics</u>

Capturing the knowledge and experience of the voters is an important part of the qualitative decision making exercise. Differences of opinion will occur based on the differing background and expertise of these people. However, it is important to ensure that the assumptions and information being used to facilitate the choices are consistent amongst all the members of the group. For that reason it is necessary to examine the voting results and to flag any possible deficiencies for further examination.

This verification can be performed from a simple case by examining visually the distribution of the votes. In this case the possible answers and the frequency with which those answers appear are plotted on a graph, and certain patterns can be seen which identify possible problems in the voting formulation. An example of several of these distributions is given in Figure 14. Distribution A shows the condition where all the voters agree on the impact of the relationship which is the ideal condition. Distribution B shows a normal distribution with the voters all towards the same side of the voting scale.

Distribution C represents a clear problem for the computation of the voting distribution as the voters are clearly at odds with one another. One group believes there is a Strong Negative impact and the other a Strong Positive and, if there are equal numbers on either side, then the resulting median or mean would both result in a value of No Impact. This discrepancy is most likely due to a misunderstanding from the voters on which direction is positive and which is negative. In such a case the facilitator of the workshop can address these issues in order to clarify the definition and institute a revote. Distribution D is a uniform distribution of votes across the entire spectrum of impact and most likely represents a lack of available information about the program or attribute being voted.

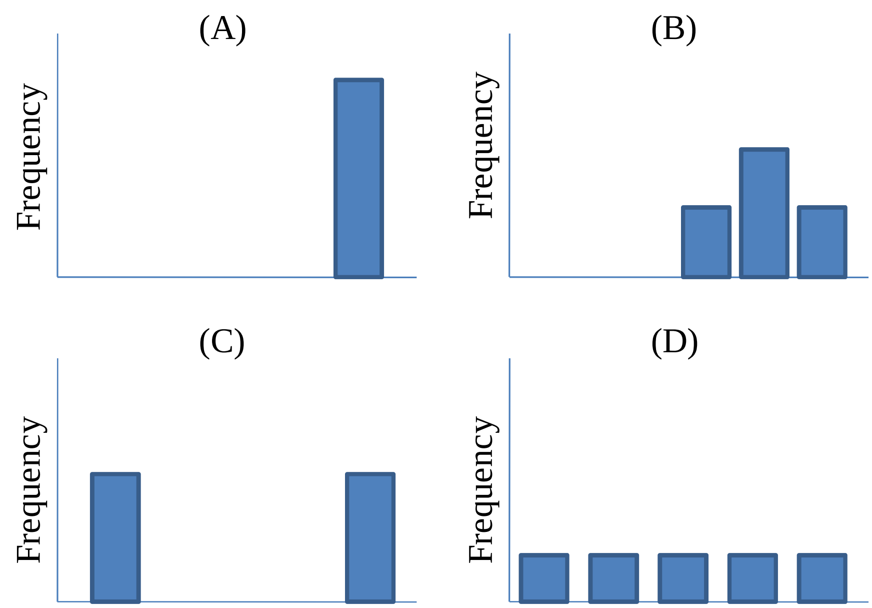


Figure 14: Example Voting Distributions

Visualizing the distributions for determining which issues are present takes time and incurs a judgment call on the part of the reviewer. When plotted in real time in the midst of a workshop for NGT, this is useful for catching problems immediately after they occur so a remedy can be undertaken. However, in the case of Delphi or online questionnaires, the reviewer will possibly have hundreds or thousands of votes to examine. Doing this one at a time via histogram is impractical, and instead, it is possible to statistically represent these different cases and determine which ones should be corrected based on the resulting values. The framework behind performing this analysis is to fit a Beta distribution to the voting sample data.

Beta distributions are represented by the equation:

$$f(x) = \frac{x^{\propto-1}(1-x)^{\beta-1}}{B(\alpha,)} \quad (8)$$

$\alpha > 0$ shape parameter

$\beta > 0$ shape parameter

The shape parameters represent different types of distributions such that determining the shape can be done without visually examining every one. (NIST/SEMATECH 2006) An illustration of the shape parameters and the resulting Beta distributions is shown in Figure 15. The advantage to moving to a numerical framework is that results can be generated in a rapid manner which would allow the workshop facilitator to address misunderstandings while the voting is still being performed.

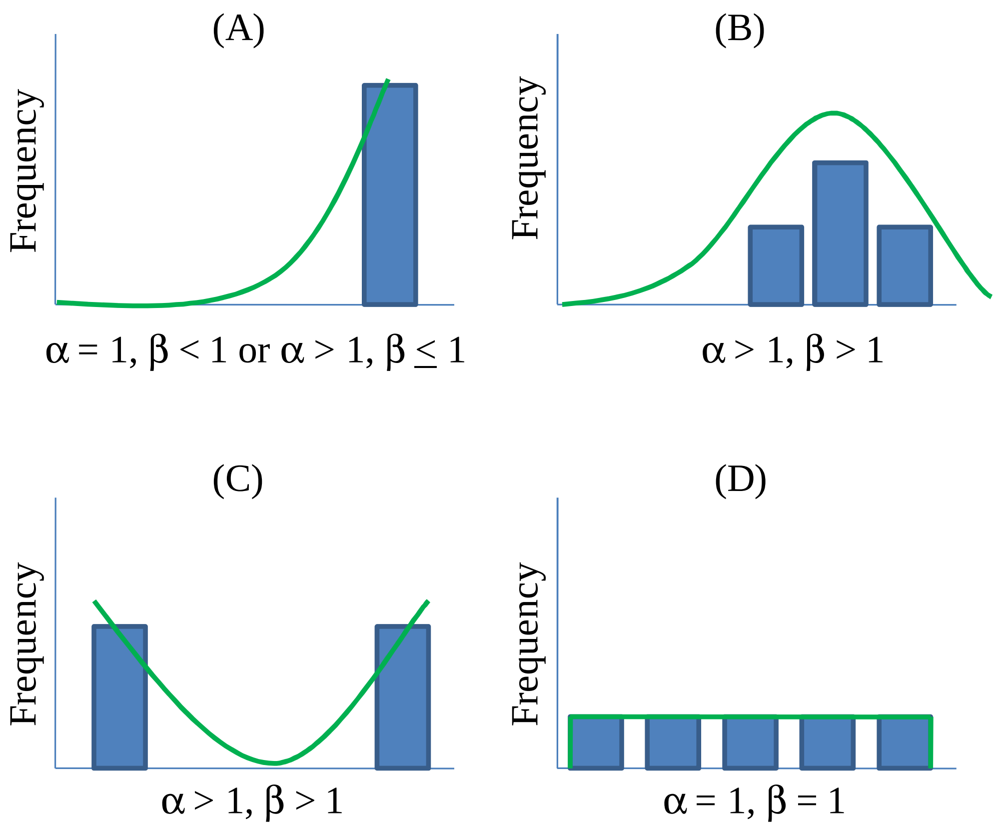


Figure 15: Beta Distribution Shape Parameters

<u>Vote Compilation Statistics</u>

Assessing the shape of the voting distribution allows those performing the workshop facilitation to ensure that the group is on track with its understanding of the relationships being addressed. The second step to determining the will of the group is to obtain a single deterministic vote out of the voting distribution. There exist two different calculations for performing this, the mean and the median.

The mean of a distribution is the expected value that is returned. Because this is determined by not only the number of points but also the distance from the other points, it is entirely possible for a single voter whose judgment is radically different from the rest to skew the mean by a great degree. This could occur due to a misunderstanding which only that one person has, or it could be due to bias. To account for bias the trimmed mean is introduced to eliminate a certain number of votes on either side of the distribution and compute the mean from those remaining. Such a technique is used in the world of Olympic judging where the highest and lowest scores for a figure skater are eliminated and the score based on the rest.

A special case of the trimmed mean is the median. This calculation excludes all but a single point in the case of an odd number of samples or two points for even numbers. The resulting point is one in which an even number of votes will exists on either side of the distribution. This technique eliminates the possibility of bias or misunderstanding greatly influencing the final value. (Hurley and Lior 2002)

Program Information

In addition to the relationships between the programs and the attributes, there is also a substantial amount of information which the decision maker will need to be able to access in order to create a solid business plan. Cost information is needed for assigning budgets appropriately. Schedule and milestones are needed in order to reach certain capabilities at times which are advantageous to the organization. Risk must be captured in order for the decision maker to balance it appropriately with the benefits possibly provided. All these elements are needed from the program managers, and eliciting it can be a difficult process.

Eliciting data from the program managers must be cost effective for the organization in terms of the amount of time devoted to it while still obtaining the quality of data needed to ensure that planning is performed to a certain standard. In addition, it is necessary to eliminate as much bias possible to ensure that the information accurate. While there exist many suggestions for creating a good survey, it is important to make sure that the elements fit the type of data which is being sought.

The format of the questionnaire is an important feature which cannot be overlooked. The questions should be ordered in such a way as to keep related material is the same proximity. While scales and “yes” or “no” answers may be required, “to allow respondents to expand upon answers and provide more in-depth responses, free text response or open questions may be included.” (Rattray and Jones 2005)

Another aspect of a successful questionnaire is the idea of pretesting or performing a pilot process. This is when a form is sent to a small sample of the people who will receive the final version and who are asked to complete it and return it along with a series of questions about the difficulty and effectiveness of the how they filled it out. This allows the facilitators to see possible problems or inadequate definitions that may have been provided and to rectify these prior to the final version being dispersed.

Step 3: Concept Generation

For most applications there will not exist a single program which meets all the needs for an organization’s vision. Rather, it is a combination of several into a program portfolio which will ultimately serve as the final selected concept. In the current formulation of the Strategic Planning methodology the use of portfolios is not as robust as would be desired. Programs are treated as separate pieces which are ranked and assessed before being combined by allocating resources to those which are the highest ranked. Because of this ambiguity between the generation of concepts and the evaluation, these areas are best combined for the purpose of strategic planning and resource allocation.

Step 4: Concept Evaluation

Evaluating the concepts and determining the portfolio of programs which best meets the needs of the organization vision is one of the final steps. Many different methodologies exist to make this determination based on what types of information are available and what kind of selection is required. As discussed previously, MADM techniques are useful for ranking and evaluating the order of several different alternatives while MODM instead optimizes the objectives of a concept to create the best alternative. MADM techniques have been used in previous application of the strategic planning methodology, but the lack of focus on creating a portfolio of programs has led to an inability to capture the portfolio and family of programs concept.

Research Question 5: How can technology interrelationships be captured adequately?

MODM Techniques

In any decision-making process there are some tradeoffs which must be made between competing outcomes. The benefits and cost of any portfolio behave such that gaining improvement in one will likely incur degradations in the other. It is the job of the decision maker to make the necessary tradeoffs between these responses to ensure that the organization goals are met. Such a decision requires knowledge as to how the responses interact and how much benefit can be made in one by sacrificing cost in the others. In order to quantify these tradeoffs a Pareto Front can be made be made and represented that shows the limit of design choices that are feasible (Roth, et al. 2002). An example Pareto Front is illustrated in Figure 16.

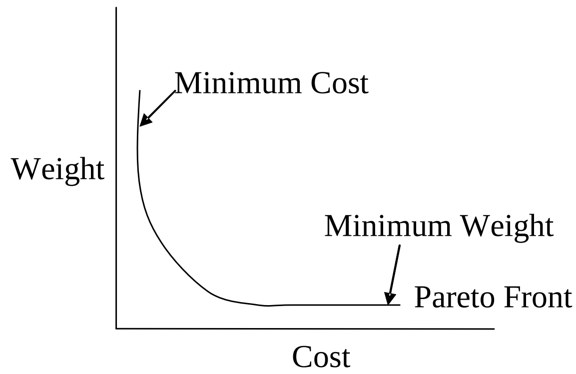


Figure 16: Example Pareto Front

Performing this objective analysis often utilizes an optimizer which seeks to find the best values for a variety of variable which produce the best response. Many different kinds of optimizers are available, and the choice of which one to use is based upon the complexity and characteristics of the problem being addressed. Whether constraints exist, variables are continuous or discrete, and how much time is allotted for performing the analysis are just some of these consideration. The problem of optimizing a portfolio has a unique set of these characteristics which will determine the appropriate method. The first is that the inclusion or exclusion of a technology is a discrete variable. Another is that due to the need for the decision maker to make real time changes to a variety of settings and re run the analysis, the methodology should be decoupled from the goal importance values or weights in determine the optimum solution. For the same visualization reasoning ,the use of methodology should be either a one-time investment or extremely quick based on changes made by the decision maker.

<u>Multi-Objective Genetic Algorithm (MOGA)</u>

In nature, evolutionary processes tailor organisms to best make use of the environment in which they live. Creatures which are more fit reproduce in greater numbers and are a dominant species while those that are less fit die off and become extinct. Genetic Algorithms (GA) attempt to utilize these same processes to optimize a solution for a given mathematical problem. Just as in nature, the basic building block of the GA is the “chromosome” which represents the settings of the independent variables of the optimization and a separate solution to the problem. While a chromosome may contain continuous values, it is more common to represent the independent variable settings as a binary string in order to simplify the evolutionary processes that are applied (Gen and Cheng 1997).

Just as many different organisms exist in a certain area, several different chromosomes are put together to create a “population”. It will be within this population that the chromosomes will be evaluated and the most fit members given preference for the next generation. Ranking of the members of a population takes place in a procedure called selection where the fitness is calculated for each chromosome. The fitness is the measure of how good each chromosome is according to the interests of the person setting up the problem and, for a simple optimization problem, could be the objective function value.

In nature, organisms that survive the longest have the highest chances of reproducing and passing on their genetic makeup to the next generation. GAs work in a similar fashion with each chromosome given a certain probability that it will be chosen for reproduction, and higher fitness values given a higher probability. Also, just as in nature, offspring are genetic combinations of the parents. In GAs two parents chosen for reproduction have parts of their chromosomes mixed in order to produce an offspring for the next generation. For binary chromosomes reproduction is done by using crossover which is illustrated in Figure 17.

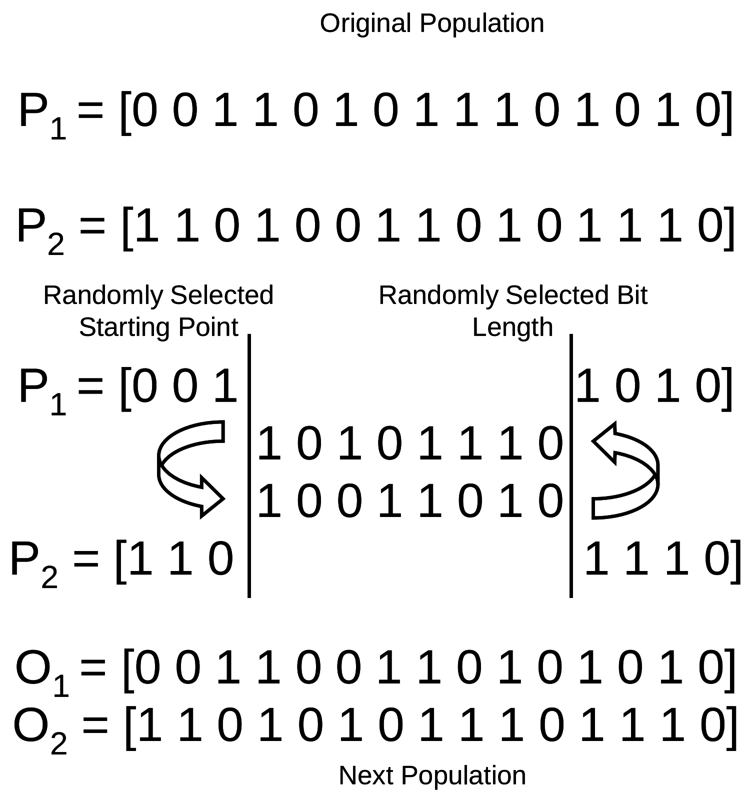


Figure 17: Crossover for Genetic Algorithm Reproduction

In addition to selection and reproduction, the evolutionary process of mutation is introduced into the GA in order to introduce traits into a population that otherwise would not exist. Since reproduction only produces offspring that are based on the parents, if a certain value in the chromosome is not found anywhere in the parent population, then it will not be anywhere in the offspring. Mutation randomly switches a bit in a chromosome to its opposite value to try to reintroduce genetic diversity.

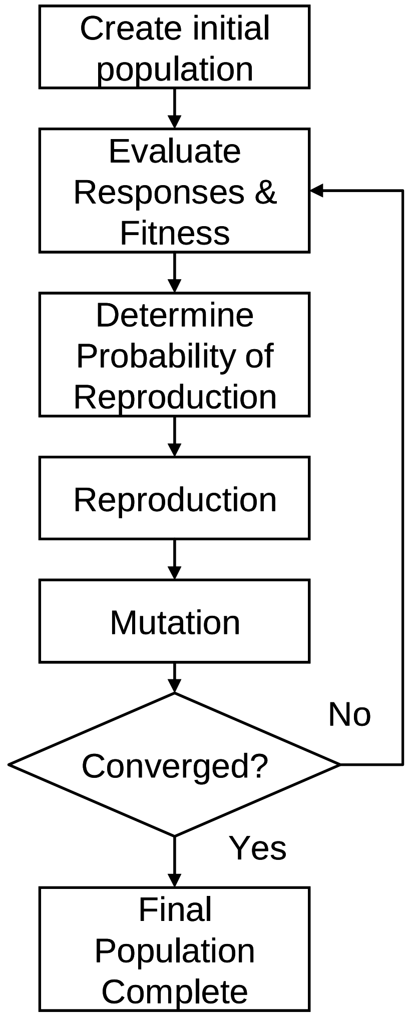


Figure 18: Genetic Algorithm Flowchart

These evolutionary processes of reproduction and mutation make Genetic Algorithms very well suited to multimodal problems because the randomness present allows them to climb out of local minima in a search for the global optimum. However, because the selection is based on a single fitness value, constrained optimizations are difficult for GAs. Previous studies have utilized a penalty based approach which lowers the fitness value for chromosomes which violate a constraint. This approach has several drawbacks depending on how large the penalty is compared to the objective function. If the value is large, then good traits that minimize the objective function can be lost as a very low fitness is assigned for a slight violation of the constraint boundary. A small penalty could lead to the finding of an “optimum” solution that is not feasible if the benefits in the objective function outweigh the negatives of constraint violation.

Gene correction is another method for handling constrained optimization within a GA and is put forth in (C. M. Raczynski, et al. 2003). In this procedure, prior to evaluating a chromosome for its objective function value, independent variables that do not meet constraint values are changed to be in feasible space. This has the benefit of always meeting constraints whenever the call is made to evaluate the objective function. By ensuring such feasibility the chances of code failure are reduced and time is not wasted on unnecessary design evaluations.

The fitness value of a traditional GA is either a single response value or a combination of several responses in a weighted, non-dimensionalized objective function value. The disadvantage of this method is that the designer must determine the weights of importance of the responses prior to having any knowledge of the behavior of the problem. In order to minimize multiple objectives a different fitness value calculation can be employed. This method, known as Multi-Objective Genetic Algorithm, utilizes the concepts of dominant and inferior chromosomes to minimize all the responses of interest (Yang, Yeun and Ruy n.d.). A dominant chromosome has at least one response value that is better than all the other chromosomes in its population. Chromosomes which do not meet this requirement are called inferior. In this MOGA procedure, the fitness value is not calculated but assigned, with dominant chromosomes given significantly higher fitness than inferior ones. This will lead to minimization of each response without needing any weighted objective functions.

Step 5: Make a Decision

With the problem defined, information gathered, concepts generated and evaluated, the final step in the process is to actually make the decision. An optimizer or ranked sorting of technologies should never be used to take the human out of the process but, rather, to provide information and tradeoffs which make a more informed selection possible. In order to accomplish this, it is necessary for the decision maker to have all the information generated in the previous steps compiled in front of them. This is done in the form of Decision Support Systems (DSS) and visualization techniques.

Research Question 6: How should the performance data be put in front of the decision makers in order to give them information that will be the most useful?

Decision Supports Systems

A decision support system is a computer based environment designed to aid and improve the decision making process. This idea first came about in the 1960's when the ability of computers to synthesize and condense large quantities of information allowed the decision makers to see trends in their business data and make decisions accordingly. DSS theory stems from the belief that in making a decision there are both structured and unstructured elements. The structured elements are things such as the cost data or other numerical information which a computer is extremely efficient at processing and understanding. The unstructured elements are those which cannot necessarily be quantified but greatly influence whether a project fails or succeeds, such as personnel interactions, organization politics, and other qualitative ideas. These elements are best handled by a human so that a DSS does not attempt to solve the problem itself but, merely inform and aid the decision maker (Arnott and Pervan 2005).

DSS's consist of three main components. The user interface provides the interaction between the system and the user. This includes the visual representation of the data as well as controls from which the user can change and manipulate various models being employed in the background. The second component is the database manager which contains all the compiled information and dispenses it to various calculations and models as the user sees fit. The third are the models themselves which represent the data in various ways to determine underlying meaning which would not be evident from just visualizing the data itself directly. All three of these components must work together and interact in order to comprise a successful system (Ariav and Ginzberg 1985).

User Interface

The purpose of a DSS is not merely to simply display the data but also to aid the decision maker by helping to visualize trends. In many cases this means that the representation of a set of data is expressed by other means than just a table or chart. As Edward Tufte explains, "Often the most effective ways to describe, explore, and summarize a set of numbers is to look at a picture of those numbers." (E. R. Tufte 1983) Visualization is defined by the National Science Foundation in its seminal report "Visualization in Scientific Computing" as "a tool both for interpreting image data fed into a computer, and for generating images from complex multi-dimensional data sets." (McCormick, DeFanti and Brown 1987) Hence, visualization is not merely a way of seeing the data but of understanding the relations and hidden properties that it represents.

One of the main questions which the decision maker needs to answer is "Why is one program to be selected over another?" As Tufte writes, "The fundamental act in statistical reasoning is to answer the question 'Compared with what?' (E. Tufte 2006)" Many different sets of data may need to be made in the course of a strategic planning or resource allocation approach. Comparing potential products against each or against a competitor in terms of performance could be such an exercise. This act of comparing two or more things is facilitated greatly by the use of a strong visualization environment. In particular, bar chats allow the viewer to understand and comprehend the comparison being made better than pie charts or line graphs. (Simkin and Hastie 1987) This use of line length for comparison is further supported by Weber's Law which states that the perception of the difference between the lengths of two lines is more related to the ratio of the difference than to the overall length of the lines. Hence, the comparison of a .75in line to a .70in line would be equivalent to that between 75 in and 70 in lines. (Cleveland and McGill 1987)

The second type of information which will need to be presented to the decision maker is that which provides reasons, causes, or explanations of events or decisions. The trends which can lead to these determinations exist within the data, but a good graphical representation can allow the information to be more easily recognizable to the decision maker. One of the most common explanations that a manager may wish to see in this strategic planning formulation is why one technology scores better than another. The calculations behind the benefit score exist, but allowing the user to query this in an interaction fashion can provide greater insight.

Ultimately the display of the information in the DSS should be based on what questions are being answered. Tufte writes: *Thus the first questions in constructing analytical displays are not "How can this presentation use the color purple?" Not "How large must the logotype be?" Not "How can this presentation use the Interactive Virtual Cyberspace Protocol Display Technology?" Not decoration, not production technology. The first question is 'What are the content reasoning tasks that this display is supposed to help with?'* (E. Tufte 2006)

Hypotheses

- Observation 1: No comprehensive investigation has been performed to determine the best way of creating the prioritization of the goals to the world scenarios.
    - Research Question 1: How can the prioritization of the goals to the world scenarios be performed better?
        - **Hypothesis 1: For applications with large numbers of goals and world scenarios a cumulative voting technique for prioritization will allow for effective overall benefit calculation.**
- Observation 2: Relationship values should be obtained in such a way as to eliminate statistical bias.
    - Research Question 2: What voting techniques are appropriate for collecting information from Subject Matter Experts?
        - **Hypothesis 2: For implementations with short timeframes Nominal Group Technique will minimize the bias in capturing the opinion of a group of Subject Matter Experts.**
    - Research Question 3: What sample size is appropriate for different voting techniques?
        - **Hypothesis 3: Estimating the standard deviation of the sample distribution and computing a sufficient sample size will allow the planners to optimize the resources required to facilitate the voting of the Subject Matter Experts.**
    - Research Question 4: How should votes be statistically compiled in order to distill the opinion of the group?
        - **Hypothesis 4: By fitting Beta Distributions to the voting sample of the Subject Matter Experts, discrepancies and misunderstandings can be captured and clarified.**

- Observation 3: Program interrelationships can be present in a portfolio and are not accounted for in the current methodology.
    - Research Question 5: How can program interrelationships be adequately captured and used to create portfolios?
        - **Hypothesis 5: Utilizing matrices of program interrelationships combined with a Multi-Objective Genetic Algorithm allows for a portfolio of programs to be optimally created in order to create potential combinations for the decision maker.**
- Observation 4: Organizations have a variety of information which can be used to make decisions and any methodology must be able to address multiple criteria in a single methodology.
    - Research Question 6: How should the performance data be put in front of the decision maker in order to give them information that will be the most useful?
        - **Hypothesis 6: Creating a structured, interactive Decision Support System will allow the decision maker to assess tradeoffs and visualize portfolios of programs in order to make a traceable, accountable, and comprehensive resource allocation.**

CHAPTER 4

FORMULATION

While a general formulation exists which has been used for strategic planning and resource allocation in the past no formalized process has been created to connect all the pieces. In addition, the current methodology has significant gaps in its overall application which precludes its use in some situations. The answers to many of these gaps were identified and detailed in the previous chapter, and this chapter will seek to outline a methodology which will formalize the process into a comprehensive one which provides traceability, adaptability, and dynamic resource allocation and decision making. This new methodology called Strategy Optimization for the Allocation of Resources (SOAR) is shown in Figure 19.

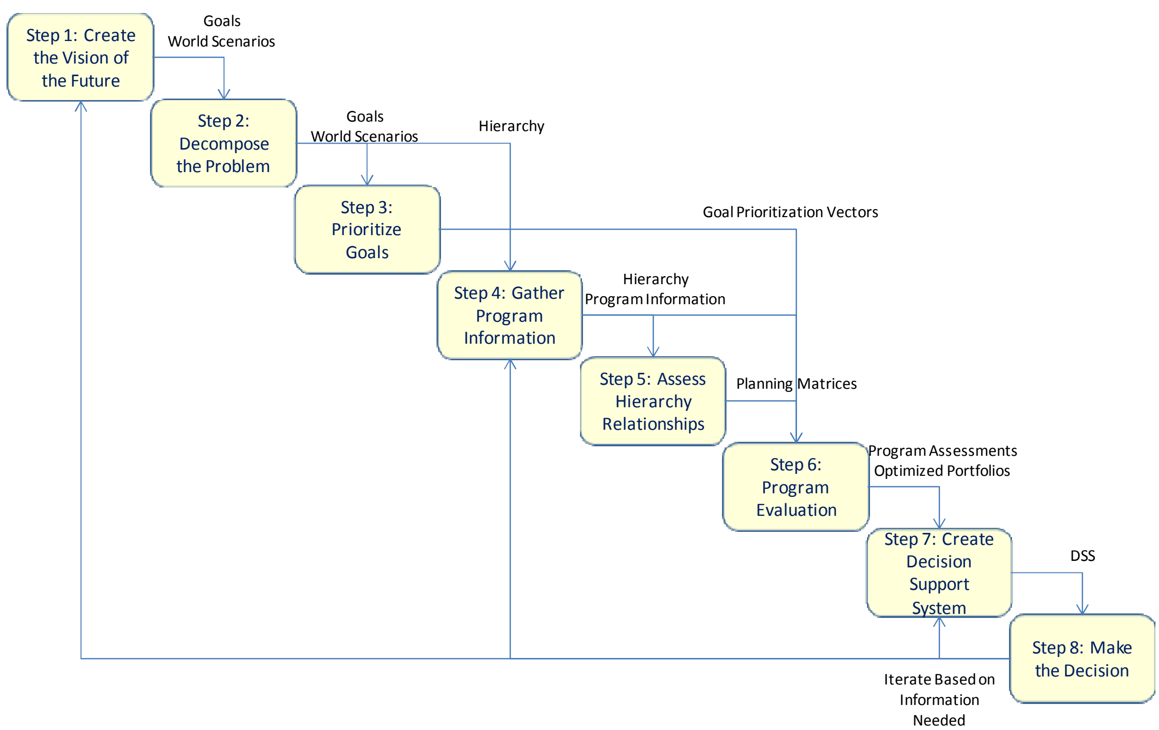


Figure 19: Proposed Process Overview

Step 1: Create the Vision of the Future

The first step in the SOAR methodology is to create the vision of where the organization should go in the future, and what the difficulties or advantages the world environment may have. While the final strategic plan will be a fully fleshed out and comprehensive framework, the vision is by no means well defined. When a new CEO or director takes charge of the organization, they bring with them a view of how the company should position itself,, and this can formulate a vision. It is the responsibility of the strategic plan to take this broad outline and to identify the traits of the organization and the world environment which have the greatest impact upon the vision. Identifying the strengths of the organization allows the vision to be crafted to best take advantage of these, and weaknesses allow management to either avoid these areas or plan for increases in capabilities to eliminate them.

Goals are a set of independent traits of the organization directly tied to the strengths and weaknesses of the organization that will be used to assess the impact that various programs and activities are having on the vision. Once management has established the statement of the future, then facilitating a workshop and using affinity diagrams and other brainstorming techniques will allow the planners to create this list. The level of fidelity of the goals should be brought to the same level, if possible, in order to make comparisons and tradeoffs between them into useful concepts. This can be accomplished through the use of interrelationship digraphs to map the interdependencies amongst the goals and to determine if any of the connections are strong enough to warrant a rearrangement.

World scenarios allow the organization to frame the potential opportunities and threats to the organization and its vision. Due to the “bounding” nature of the world scenarios, a spectrum of possibilities should be analyzed. In addition to the most probable outcomes, the planners should also create frameworks for those events which would have great impact but are not as likely to occur. Compiling a probability of each world scenario occurring would allow the decision makers to better plan for the most likely future while still maintaining a view for less likely, but more serious possibilities. Understanding what the world scenarios entail will also aid the planners in compiling the top level goals of the organization by ensuring that the most significant impacts, which a particular scenario has, are captured in the list of goals.

In addition to the world scenarios and goals, the decision maker should also identify areas in which programs differ which could affect their prioritization. It is important to identify what characteristics or traits such as risk, probability of success, or technical discipline might be important metrics to be included in the final visualization. Making this determination early on the process allows for the planners to capture the necessary data to facilitate these views at appropriate times.

Step 1 Summary

Inputs: Organization Vision

Techniques: Brainstorming techniques and SWOT analysis

Outputs: Top level goals and list of possible world scenarios

Step 2: Decompose the Problem

The second step in the methodology involves taking the goals defined in Step 1 and creating a hierarchy of traits for assessing the impacts of the programs. Due to the vague nature of the top level goals, it is often difficult and impractical to relate the programs directly to these. Several levels of increasing fidelity are needed to make intelligent and well reasoned relationships. What type of programs are being assessed also provides for different kinds of hierarchies to be created. The hierarchy should be constructed differently for programs aimed at specific products versus those which are more organization wide.

If the purpose of the strategic planning exercise is to determine which programs or technologies affect a specific product or family of products, the decompositions should takes this into account. The goals of the organization should stay at a fairly broad categorization, but the intermediate levels between these and the programs should be focused on the attributes and functions associated with the specific products. This type of analysis will not only provide prioritization of the programs but will also allow the decision maker to visualize how the products affect the goals differently.

Planning exercises which are independent of products require a more top down approach. Without the specific physical decomposition a more generic functional decomposition is needed. First, the top level goals should be fully explained and defined by the team. Traits of these goals should be brainstormed and placed into groupings based on the level of complexity and description. To aid in this description, interrelationship diagraph can be used to find all the connections between the brainstormed elements. Those pieces which have the most interaction coming in to them rather than going out can be placed at the highest level since they are being affected more than they affect other elements.

Step 2 Summary

Inputs: Top level goals and world scenarios

Techniques: Brainstorming techniques and interrelationship digraphs

Outputs: Decomposition from goal level to programs

Step 3: Prioritize Goals

This step takes the top level goals defined in Step 1 and refined in Step 2 and captures the importance values that each has to the defined world scenarios. This will be accomplished by using a group of Subject Matter Experts to weight the values based on their individual knowledge and experience preferably in a workshop environment if resources are available to accomplish this; however, online questionnaires are possible should the circumstances of the organization not allow this. Depending on the number of votes which are needed based on the goals and world scenarios, the use of Pairwise Comparisons or Cumulative Voting is required.

Pairwise Comparison Voting for Small Numbers of Goals

For problems where the availability of the voters is not hampered by the number of votes to be taken, the use of a pairwise comparison methodology allows for the relative prioritization needed in this step. The first objective is to determine the number of people which should be utilized for the voting sample. This is accomplished according to the equation 4 in Chapter III where the terms are based on an AHP application. The alpha level to be used is 0.05 from Bartlett, Kotrlik, and Higgins which gives a t value of 1.96. The acceptable margin of error is up to the decision makers as to how much difference in the final mean or median is enough to ensure that the results are useful. The estimate of the standard deviation should be the scale of the vote divided by the number of values which encompasses almost all of the sample points. (Bartlett, Kotrlik and Higgins 2001)

With the number of samples defined the vote can be taken in the workshop with each of the voters comparing the goals for each world scenario. Goal A is given a value based on how much more or less important it is compared with Goal B for a given scenario. Once a full matrix has been constructed by each voter then the result can be compiled into a full sample and assessed. Calculating the standard deviation of the distribution allows the planners to better assess whether an appropriate sample size was utilized. By replacing the estimated standard deviation in the sample size equation previously discussed with the actual value the number of required votes can be calculated again. If this number is less than or equal to the number of actual participants, this step is complete; however, if it is not then the difference in the two numbers reflects how many additional votes should be needed in order to bring the sample within the appropriate margin of error.

Once the voting for all the pairwise comparisons has been completed, the importance vectors for all the goals can be computed. This is done according to the AHP methodology by computing the eigenvalues of the matrix which gives the relative importance values of each of the goals.

Cumulative Voting

The use of the cumulative voting technique is applicable for the prioritization of the world scenarios when the number of votes necessary to complete the pairwise comparison matrices is too great for the amount of time or resources that the organization can devote to the problem. As with the previous technique, the first step is to determine the number of people which are required to create an appropriate same size. The alpha level will set the same as it was for the pairwise comparison case. The only major difference for cumulative voting is in the scale of the votes. Where AHP uses a 1-9 and 1/1 - 1/9 scale cumulative voting uses a 1-10 selection of importance. This difference reflects a substantial difference in the estimated standard deviation of the resulting distribution.

Once the group has been assembled for the voting and the briefing has been given on the definitions of the goals and world scenarios, the voting process will take place. Individuals will be assigned a number of points dependent on the number of goals to be prioritized. A good rule of thumb for the number of points is that it should be twice the number of goals. This allows for the voter to give some importance to each while still retaining the ability to prioritize some over the others.

Step 3 Summary

Inputs: Top level goals and world scenarios

Techniques: Analytic Hierarchy Process and survey sampling techniques

Outputs: Importance vectors for goals by world scenario

Step 4: Gather Program Information

In this step the information on each program is gathered which will facilitate the completion of the rest of the process. There are two types of data which should be sought: that which will aid SME's in assessing the impact and that which will be used directly as secondary information for resource allocation. Both types should come from those with the most knowledge of the programs themselves in order to get the best quality.

Impact assessment data is that which the voters will later use to create the relationships between the various levels of the hierarchy. Of primary importance is a solid description of not just what the program aims to do, but also how it seeks to go about it. This "how" information allows the SME's to assess not only the primary benefits which will be derived from the completion of the project but also secondary benefits and costs which will result from the application. It is important that when this information is compiled that the planners ensure that all the programs have the same level and quality of data. Too little depth or poor quality in the description can leave the voters uncertain as to what and how the program will accomplish its desired purpose. Also, those whose descriptions seem more like a sales pitch than an informational briefing can induce improper bias into the process.

The second type of data to be gathered from the program experts is nonstandard metrics which will be used by the decision makers in the resource allocation and planning phase. Benefits to the vision and cost are only two of the many different kinds of data which can inform a well made decision. Taking into account the risk, for example would show an organization leader that while a particular program may have great benefit to the organization, the probability of it being successfully implemented is quite small. In addition to risk other secondary information may also include organization codes of different types of funding or resources, whether the proposed program is new or an extension of current work, or any other data which is very specific to a particular application.

The means to capture this information should be in the form of a questionnaire which allows the responder to write detailed explanations of only select preset options where desired. The length of the questionnaire should be based on gathering the required information without overburdening the individual who will fill it out. The more programs that an individual is responsible for responding on behalf of, the less information should be required. Pretesting the format of the questionnaire with a small group of respondents is a very important step to ensure that the explanations of what type of information is clear enough to gather good responses. Any terms which may not be directly understood by the respondent, such as attributes which were created for this process, should be defined clearly and consistently.

After the completion of the form by the program experts, it is necessary for planners or organization individuals from a higher level of management to review the information and ensure that it is of good enough quality to proceed. The descriptions of the program should be examined to ensure that it is of the appropriate fidelity to give the SME’s a fair idea of how the application will affect the attributes. The cost and risk data should be judged by an impartial group to determine whether it is unbiased or whether it has been given a generous slant in order to appear better. Once the data has been compiled, it is possible for the impact relationships to be addressed.

Step 4 Summary

Inputs: System level attributes and what information the decision maker desires for resource allocation

Techniques: Questionnaire creation techniques

Outputs: Compiled programmatic information

Step 5: Assess Hierarchy Relationships

For each level of the hierarchy established in Step 2, qualitative relationships will need to be created which link the elements of the levels to those of the adjoining ones. For a goal – attribute – program decomposition this would result in two separate planning matrices of goals versus attributes and attributes versus programs. This methodology focuses on applications which lack the ability to create modeling and simulation environments or gather experimental data. Because of this lack of high fidelity tools, the planning matrices will be focused around qualitative descriptions.

What type of assessment technique should be used is largely based on the number of relationships which need to be voted on and the ability to get groups of people together. Ideally the participants should be gathered together for a workshop where discussion and clarification of misunderstandings can occur in real time. However, typically a 2-3 day workshop is all the time that can be spared by the Subject Matter Experts, so anything which requires more votes than this will facilitate on offline voting methodology. An online or emailed questionnaire would be appropriate in such a case and is also necessary when the SME's are spread out geographically and the time and funds are not available to gather them together.

Voting Scale

The use of qualitative voting scales allows the voters to create the relationships between the various levels of the hierarchy in the absence of enough data to make hard quantitative judgments. The scale which is used in this methodology consists of seven levels and is listed in Table 7. The use of both positive and negative qualifiers allows for the costs which are incurred by the programs to be represented along with the benefits they provide. In addition to the “No Impact” value, the users should also be given the option of not entering a score or entering an “I don’t know.” This allows those without sufficient expertise in a certain area to opt out of having an impact rather than cast a vote they know to be flawed. The slight drawback to such a technique is reduction in the number of samples which will be present in these cases.

Table 7: Sample Voting Scale

Descriptor	Category ID#
Strong Negative	1
Moderate Negative	2
Weak Negative	3
No Impact	4
Weak Positive	5
Moderate Positive	6
Strong Positive	7

Workshop Facilitation

If the funding is available and the application permits the use of facilitated workshops provides some unique benefits to the methodology. Utilizing the Nominal Group Technique allows the planners of the voting session to perform the exercise in a structured and efficient method. In addition to these planners and the SME's, representatives of the various programs should be present in order to brief the SME's on the programs and answer any questions which may arise.

The first workshop preparation should occur well before the date of the event. Determining the participants should be done by a team of planners with a good understanding of personnel and experience. Those who are chosen should be unbiased to the programs that will be voted on and have no direct stake in which ones are included in the plan. Several weeks prior to the workshop the participants should receive an information packet containing definitions and descriptions of all the levels of the hierarchy to be voted on. Also, the descriptions of the programs submitted in Step 4 should be included in the reading packet to give a first sampling of the information which will be presented at the workshop.

The format of the workshop should generally follow a standard format. The flow of the voting and discussion should proceed from the top level down to the programs. This will allow for questions on the attributes and format of the voting to be clarified prior to the majority of the votes which takes place at the program to attributes level. To start the workshop, one of the decision makers who will utilize the results of the process should brief the methodology and reasoning in order to show the SME's the value of the coming days of work. Following this the top level goals and the level beneath them should be presented and discussed. Voting should be performed for the relationships between these 2 highest levels. This pattern of presentation, discussion and voting should then proceed for each level down to the programs.

Online Voting

If the funding does not exist or it is impractical to gather the SME's in a workshop, an online or email based questionnaire must be provided. The format of this survey should reflect the same rules as the programmatic information questionnaire from Step 4. Since this voting process takes place on the SME's own time, it is very important that the program information be readily available in the same location as where the votes will be recorded. The less time that user must spend flipping back and forth, the more chance the needed research will be performed which will benefit the final results.

Voting Review

Following the workshop or questionnaire voting session, the planners should review the voting data and determine whether revotes or further samples are required to get a clear picture of the impacts of the various levels. This analysis should start with a review of the sample distributions to determine whether the standard deviation is small enough to justify the number of participants. If this does not turn out to be true, it is necessary for the distribution of the votes to be analyzed further to determine the reason for the discrepancy.

By fitting a Beta distribution to the sample the shape can be understood and general assumptions made as to the cause of the error. The general equation for this distribution is given in Chapter III as Equation 5. The shape parameters can be estimated utilizing

$$\alpha = \bar{x}\left(\frac{\bar{x}(1-\bar{x})}{v} - 1\right) \tag{9}$$

$$\beta = (1-\bar{x})\left(\frac{\bar{x}(1-\bar{x})}{v} - 1\right) \tag{10}$$

Where for intervals of (h,l) different than (0,1)

$$\bar{x} = \frac{\bar{x}-l}{h-l} \tag{11}$$

$$v = \frac{v}{(h-l)^2} \tag{12}$$

Shape parameters which indicate a normal distribution with a large standard deviation would be best corrected by increasing the sample size of the distribution by gathering more votes. Bimodal distributions with voters taking opposing sides of the scale represent misunderstandings between the participants and should be remedied by performing a revote of those involved. Once the voting samples all fall within the specified bounds for the determined standard deviations, the relationships between the levels of the hierarchy have been completed.

Step 5 Summary

Inputs: Hierarchy of goals to programs

Techniques: Survey sampling techniques, nominal group technique, and group facilitation concepts

Outputs: Qualitative planning matrices relating the impacts of all the elements of the hierarchy to adjoining levels

Step 6: Program Evaluation

Planning requires that programs be properly evaluated in order to create a sound resource allocation. This assessment will focus on two methodologies, each providing unique measures of benefit. The first, individual assessment, focuses on sorting through the programs and ranking them based on the benefit to the goals. The second, portfolio optimization, will utilize the program interrelationships to create the optimum combination for achieving the goals within the allowable budget.

Regardless of which methodology for evaluation is used, the programs require a metric for the benefit they provide to the organization. This score is based off the planning matrices which were constructed by the SME’s in Step 5. The first step is to convert the voting scale to a numerical value which best represents the linguistic descriptor based on the application. With the planning matrices in a numeric framework, they can be multiplied together in order to obtain the relationships between the top level goals and the programs. This final planning matrix provides the metric of benefit that will be necessary in the following evaluations.

MADM Technique Selection

Different MADM techniques rely upon different kinds of data and upon various assumptions which are made in the course of creating the problem. Determining which one is applicable must be done on an individual application basis. A methodology, such as Multi-criteria Interactive Decision-making Advisor and Synthesis process (MIDAS), could provide great benefit to the planners by allowing them to identify the traits of the problem and have an appropriate technique be identified from a defined library which would provide the greatest benefit to the planning process (Li 2007). The process framework for MIDAS is shown in Figure 20.

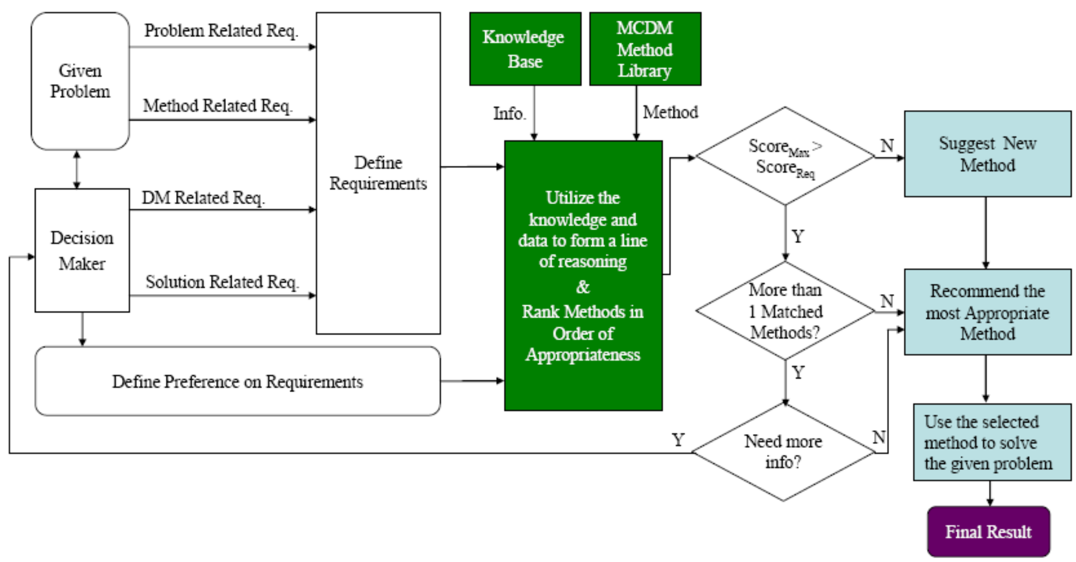


Figure 20: MIDAS Process Flowchart

Individual Program Assessment

Evaluating the individual programs and their benefit to the organization can allow the decision makers to make an informed resource allocation. This perspective is of particular consequence in the absence of program interrelationships. Ranks are calculated by utilizing the identified MADM technique where the weighting factors are the goal prioritizations for the world scenarios. Each of the programs is put in order from the greatest benefit or benefit to cost ratio down to the least value. Upon completion of this ranking the planners specify funding levels for each of the fiscal years that the decision makers are compiling a plan for.

The determination of which programs are funded is done according to the algorithm shown in Figure 21. Funding is allocated starting with the first year and the highest rated program. More money is allocated on each subsequent technology until the allowable resources are exceeded in one of the fiscal years. The program which exceeds the budget is then moved out to later years until a conflict no longer occurs or the planning years are exceeded. When this happens the algorithm then proceeds down the list until all have been assessed. This formulation allows for lower priority and lower cost technologies to have the ability to be funded once the higher priority and higher cost ones have been fully exhausted.

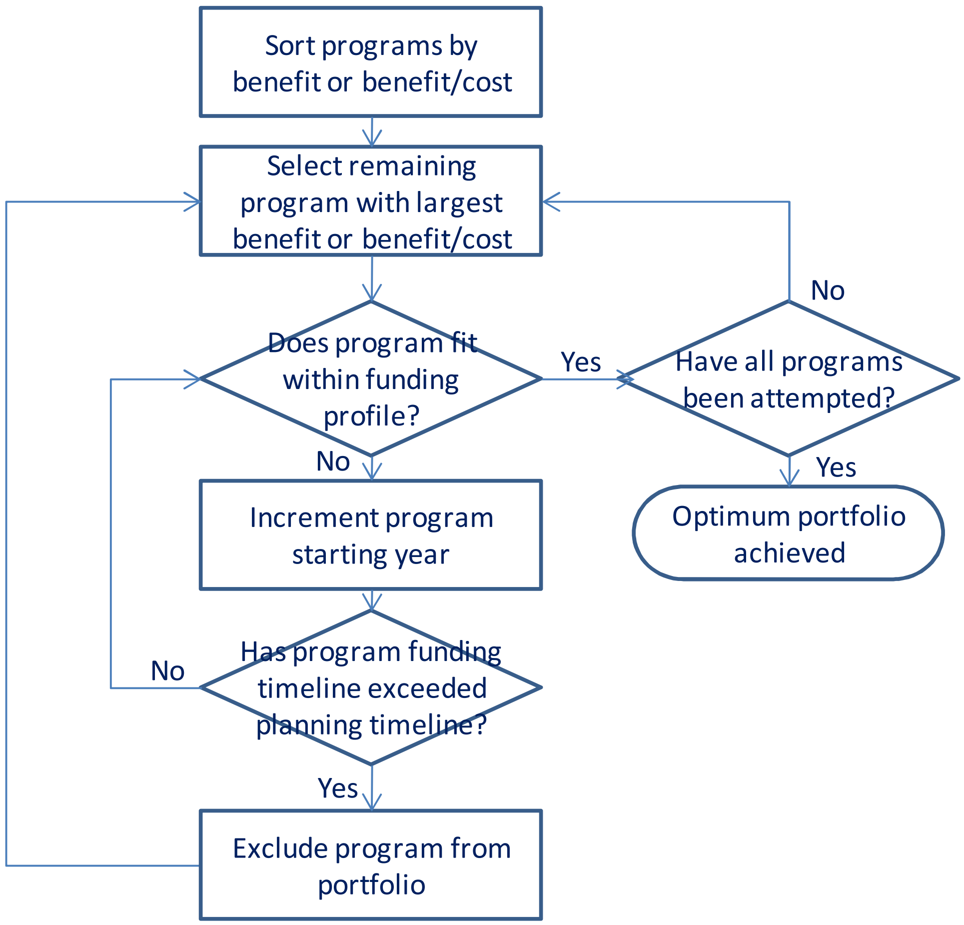


Figure 21: Individual Program Assessment Funding Algorithm

Program Portfolio Optimization

In the presence of program interrelationships the ranking and funding scheme utilized in the individual program assessment can prove extremely difficult to creating portfolios. Optimization can be used to deal with this difficulty by creating portfolios of programs while taking into account these relationships. Due to the discrete nature of the program status combined with uncertain importances of the goals, an evolutionary optimization scheme called the Multi-Objective Genetic Algorithm (MOGA) is used.

Due to the random nature of the MOGA, there are several different probabilities which must be set by the planners in order to tailor the problem to the portfolio of interest. These parameters include the probabilities of crossover during reproduction, mutation, the number of chromosomes in each generation as well as the number of generations. In addition to setting these values, it is also necessary to determine how the interrelationship constraints will be handled by the optimizer. The methodology proposed herein will create a penalty by eliminating any benefit gained from two incompatible technologies included in the same portfolio as well as any program whose enabling program is not also active. Synergistic programs will have their overall score to the goals modified based on whether both programs are included in the portfolio. Regardless of whether the benefit score is modified for a interrelationship the funding of all programs included in the portfolio will be used in the Benefit/Cost objective.

The results achieved from the MOGA are not just the single best chromosomes for each of the objectives but also the children of all the generations. These portfolios represent the mix of characteristics which will lie upon the Pareto Frontier and provide the tradeoff between the objectives which is ultimately desired for the final resource allocation. Each of the top level goals will be utilized as objectives for the MOgA along with a single Benefit/Cost objective which is introduced to keep the concept of resources present in the optimization. Graphically these points can be visualized in a multivariate analysis across all the objectives and utilizing JMP© or another data analysis program the points which fall show the best tradeoff values for two objectives can be queried and assessed across all the others. An example analysis is given in Figure 22 for three objectives two of which are constrained below certain values. The resulting area represents the feasible area from which portfolios can be chosen. The red point indicates the same data point across all thee plots and how what might be optimum for one combination of objectives may not be for the others. This indicates that a more robust and structured way of determining the optimum portfolio should be used for analyses with greater than two objectives.

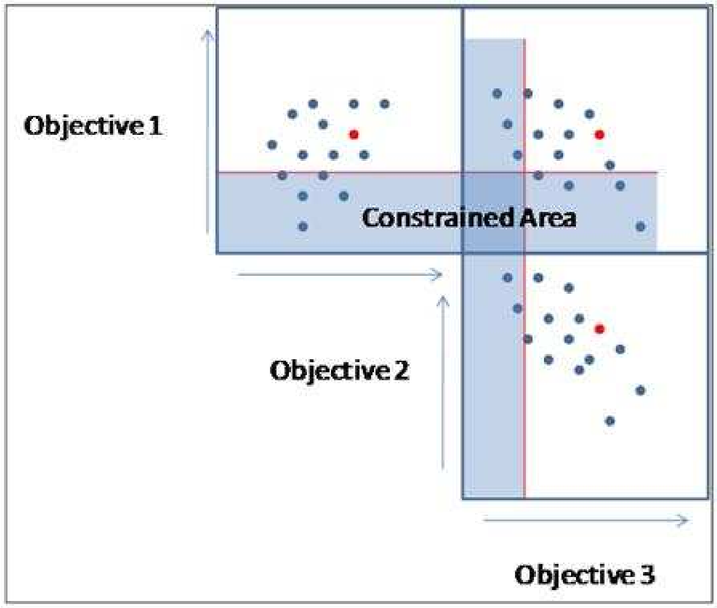


Figure 22: Example Multivariate Analysis for a MOGA

Since many applications will have more than the three objectives which can be shown graphically, it is necessary to have an algorithm which allows the user to sort through all the MOGA results to obtain the portfolio which provides the greatest possible benefit given the available funding. First, the points obtained from all the generations should be sorted based on the amount of funding that each requires. Then all the points which exceed the amount of allowable funding are excluded from further analysis. Next the portfolios are sorted based on their overall benefit score which is given from a weighted OEC where the weights are importance values of the goals as determined in Step 3. Starting with the largest value each of the portfolios is analyzed to determine whether it can be made to fit within the allowable funding profile which is provided by the planners. This fit check is performed by placing each program in the funding profile from most expensive to least and moving the start dates until they all fit. If a program cannot be fit in any place, that portfolio is eliminated and the next in the order of benefit is attempted. A flowchart for this algorithm is shown in Figure 23.

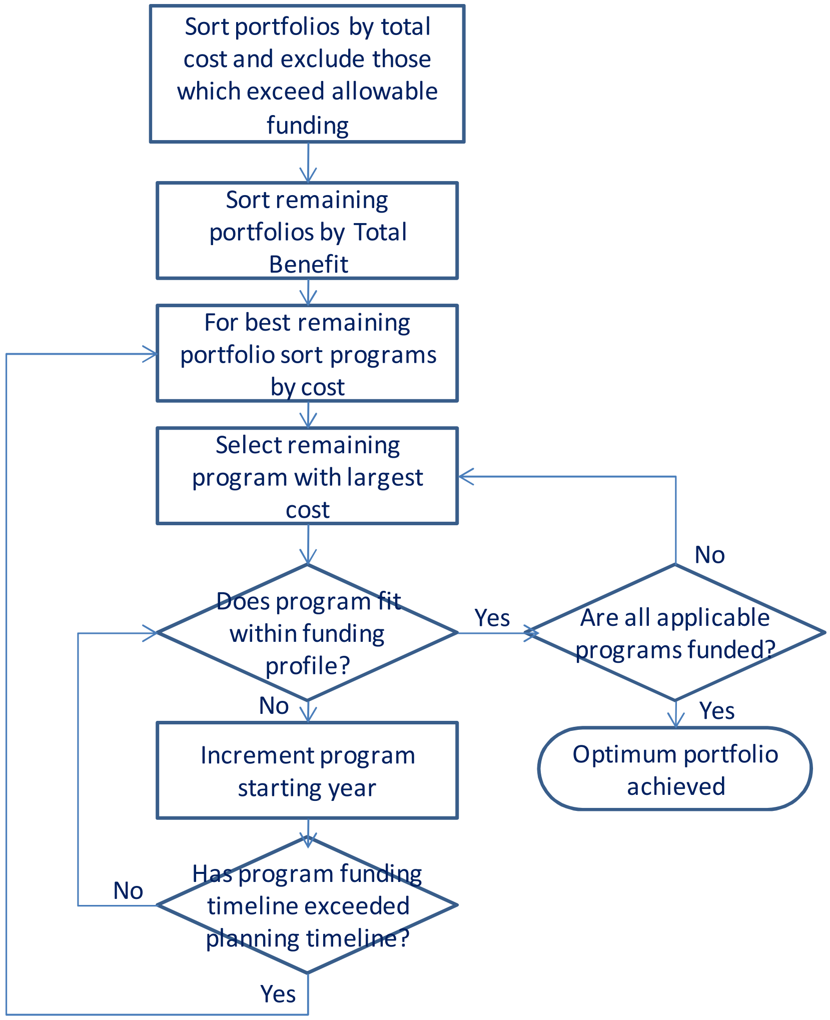


Figure 23: MOGA Optimum Portfolio Selection Algorithm

Step 6 Summary

Inputs: Planning matrices, goal importance vectors for world scenarios, and allowable funding profile

Techniques: Ranking and sorting algorithm and Multi-Objective Genetic Algorithm

Outputs: Ranked listing of programs and assessment of funding availability for them as well as optimized portfolios for the given world scenarios and funding profile

Step 7: Create the Decision Support System

With the means of evaluating the programs created in Step 6 and secondary information gathered in Step 4, it is possible to create a decision support system which brings together the various pieces of the information into a single framework. Ultimately the layout design should be based on what kinds of comparisons and trends the decision maker is interested in, which were identified in Step 1 of the process. There are, however, several types of graphs which show important parts of the process to those who will be utilizing the data.

Individual technology assessments utilizing a list of programs show how each stacks up allows the planner to see the exactly how the order comes out. In addition to a list, the benefit score can be shown in the form of a bar chart which allows visualization of the comparison between the different levels of benefit which are provided. Once the list is created various pieces of program specific data can be placed next to the ranking which allows the decision maker to see details without losing sight of the overall importance.

In addition to the visualization of information about the individual programs, there is a great deal of information about the portfolio which can aid the decision maker in forming the business plan. Understanding the total contribution of various elements to a whole is best accomplished by showing the area of the contributions. Thus tree maps, pie charts, and radargrams can provide unique insights into what component programs are giving the most benefit to the total as well as the change in the total benefit between several different portfolios. Examples of these graph formats are shown in Figure 24. In this example the area of the tree map and the area of the pie charts depict how much each of the programs contributes to the given objective. Tree maps are also useful in further breaking down the problem and showing smaller sections within the Program area to depict other sub function contributions. Radargrams show each of the objectives along the axes with the total area of the programs relating the overall benefit which a program provides to the system.

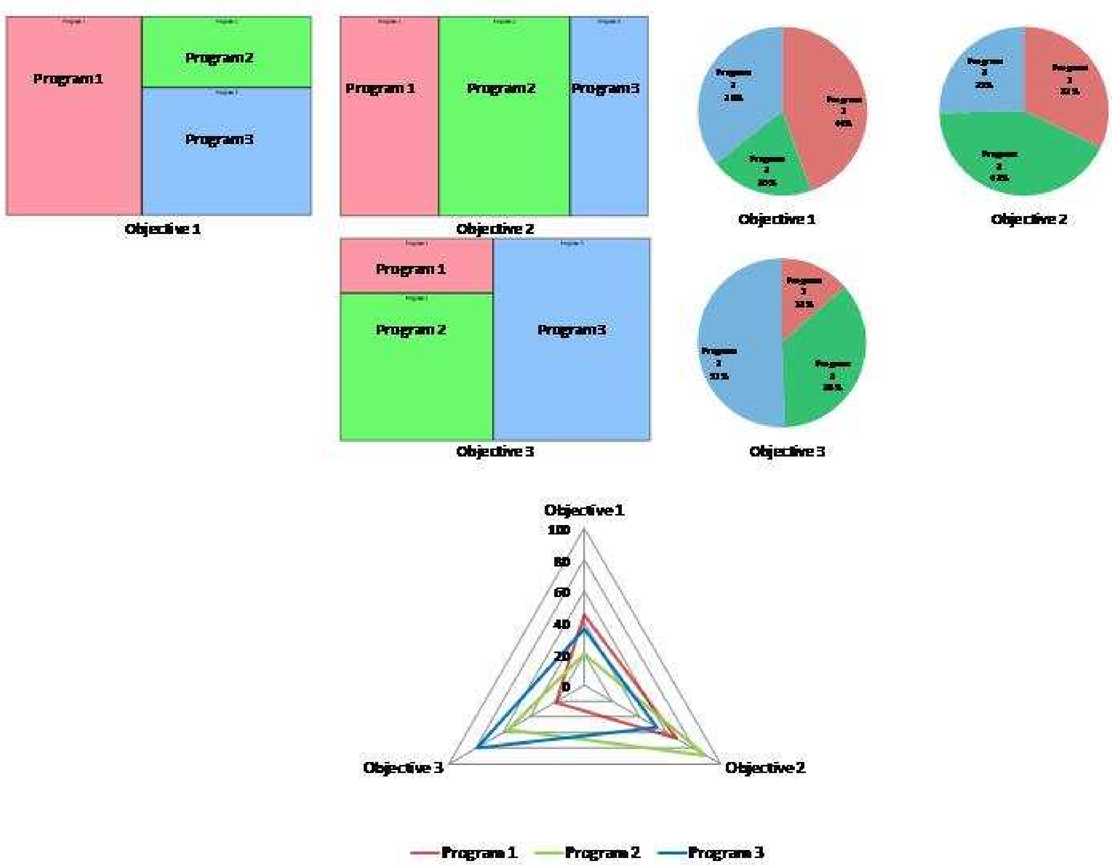


Figure 24: Sample Tree Maps, Pie Charts, and Radargram

In addition to gathering the graphical analysis together to aid the decision maker, it is also necessary to allow for tradeoffs to be made and assessed in real time. In evaluating the programs several data inputs are made, such as which scenario to base the benefit scores on and what funding profile should be planned for. These decisions can change based on the person utilizing the system, so it is necessary to allow them to be changed easily and have the calculation in the back of the system quickly update and redisplay the new information. This dynamic capability allows the decision maker not only to attempt different tradeoffs but also to perform sensitivity analysis and judge how much change there is in the portfolio between depending on the degree to which assumptions are changed. This analysis can show how much volatility the final plan has to an uncertain future.

Step 7 Summary

Inputs: Programmatic data, optimized portfolios, and world scenario mappings and information

Techniques: Visualization techniques and interface design methodologies

Outputs: Customized decision support system

Step 8: Create the Plan

The final step of this methodology is to create the plan based off the information generated. How this is accomplished is ultimately up to those involved in each application. The information generated, however, allows those involved to see how different proposed plans and program portfolios will ultimately affect the overall vision and direction of the organization as a whole. The linkage between the goals and the programs allows those involved to not just see how much benefit one concept may provide over another but also to understand why such differences exist. Seeing which attributes contribute to the goals may lead to previously unexplored areas for the organization to capitalize on in order to see greater benefit. All these explorations and more are utilized in this methodology.

Matrix of Alternatives

The methodology laid out in this chapter has provided a number of options which are applicable and necessary for certain kinds of conditions relating to the scale and scope of the problem being addressed. Choosing which combination will provide the greatest benefit to the planners and decision makers should be based on the characteristics of each which have been addressed in this formulation. In order to summarize many of these possible choices a matrix of alternatives is provided below which outlines many of the options available.

Table 8: SOAR Matrix of Alternatives

Problem	**Methodology**		
Goal Prioritization	Rank Order	Cumulative Voting	Pairwise Comparison
Hierarchy Relations Procedure	Delphi Technique	Nominal Group Technique	Online Questionnaire
Program Evaluation	Individual Program Ranking	Program Portfolio Optimization	

Iteration

The proposed methodology is not simply run through once, used to complete the plan, and then left on the shelf. It is a living process which is continually updated and varied as various elements demand. As programs become more mature, it is necessary to update the relationship data to reflect better understanding of what the final impact will be. Over time the world scenarios will become better defined and new opportunities or threats will arise. Updating this data and revising the resource allocation can keep the plan fresh and current.

CHAPTER 5

IMPLEMENTATION

The Office of Naval Research is the organization within the United Stated Navy which is tasked with coordinating and executing the science and technology programs of the U.S. Navy and the Marine Corps. In order to accomplish this task it is necessary to establish which programs and technology projects will benefit the country the most. In 2006 the Aerospace Systems Design Laboratory was tasked with aiding the Ship and Ships Systems (S3) Division of the Naval Seas Systems Command (NAVSEA) to establish a Science and Technology Portfolio. This chapter will show the implementation of the previously created process to accomplish this goal.

Step 1: Create the Vision of the Future

The first step in defining the problem is to establish the vision of the organization and relate it to what can be accomplished by the programs being investigated. The Naval Vision as outlined in the document Naval Power 21… A Naval Vision:

The hallmark of the Navy/Marine Corps team has been the ability to change, adapt and transform to meet new threats to America. Once again, our Naval team is changing in response to a new national security posture as articulated in the DoD Quadrennial Defense Review. This vision statement defines this new direction for the United States Navy and Marine Corps to continue to control the sea and to project power, defense and influence beyond the sea as part of a Joint Warfighting Team. Our forces will use the sovereignty of the sea and enhanced networked seabasing to operate without restriction. Our forward expeditionary nature will provide persistent warfighting capabilities and sustained American influence wherever we may be called to deploy. We will assure our *friends and allies, and together with the U.S. Air Force, U.S. Army and U.S Coast Guard we will dissuade, deter, and defeat our nation's enemies. Our Sailors, Marines, and Civilians will leverage innovative organizations, concepts, technologies, and business practices to achieve order of magnitude increases in warfighting effectiveness. Sea-Air-Land-and Space will be our domain. The Power of Joint Service Teamwork! (England, Clark and Jones 2002)*

While this Naval Vision related the vision of the Navy as a whole the needs of the NAVSEA Ship and Ship Systems Product Area are more specific. NAVSEA utilized this vision along with other military planning information in order to establish a set of Capabilities which would allow the organization to have the S&T necessary to fulfill the Naval Vision in the 20-30 year timeframe. Establishing the capabilities was performed by analyzing documents within the Navy to determine its strengths and weaknesses and what potential threats and areas of conflict existed for the future. By evaluating the various possible areas of conflict and future participation for the U.S. Navy a set of possible scenarios were created. From these world scenarios a set of capabilities was created which would be needed to deal with these issues. Capabilities were created which fit into several different areas:

- Speed
- Strike
- Special Operations Forces
- Survivability
- Flexibility
- Logistics
- Human Integration

- Cost

World scenarios were identified which could be used to help prioritize the capabilities for different military actions. Based off the same Naval Vision and planning documents as the Capabilities, these scenarios reflected possible types of engagements that the United States military may be involved in the future. Effort was made to place a good deal of diversity in the analysis in order to cover wholly different types of missions.

Step 2: Decompose the Problem

While the capabilities related how the world scenarios may be accomplished, it was necessary to further decompose the problem to obtain how the programs will affect these capabilities. NAVSEA has responsibility for both surface ships and submarine science and technology, so the capabilities were decomposed to both of those types of systems. Further decomposition was accomplished by the creation of a set of lower level attributes which the programs could affect. Interdependence was taken into account and minimized as much as possible in order to keep everything on the same level and the mappings between the different levels uncoupled. These attributes are given in

Table 9.

Table 9: Naval Vehicle Attributes

Naval Vehicle Attributes	Definition
Commonality/Open Architecture	Common systems or subsystems; also managed interfaces across systems
Susceptibility	Degree to which a ship can be detected, tracked, and targeted
Reconfigurability	The ability to reconfigure platforms for different missions as well as the ability to reconfigure the ship systems and subsystems to enhance mission effectiveness
Maintainability	Ability to maintain the ships systems in a timely fashion
Mobility	Speed, maneuverability, sea keeping, stability
Reliability	Probability of mission loss due to failure of Hull Mechanical and Electrical systems, also tolerance to the effects of the environment
Vulnerability	Tolerance to the effects of weapon hits
Recoverability	Ability to recover rapidly from damage
Sustainability	Ability to operate independently with minimum logistics demand also enables rapid re-supply at sea
Payload Capability	Percentage of light ship displacement and volume dedicated to mission payload
Environmental Compliance	Systems and subsystems which provide a capability to train, operate and conduct

	sustained naval operations world-wide unimpeded be national and international environmental regulations and standards

The decomposition continued down from the attributes to the programs themselves which were contained within several different Core Equity Areas. These groups represented disciplines within the Office of Naval Research (ONR) which sponsored and oversaw the work. Programs were specifically identified as Science and Technology (S&T) projects which were either in the early phases of research or were new concepts. A total of 38 technologies were proposed in the six Core Equity Areas. The final decomposition hierarchy is shown in Figure 25.

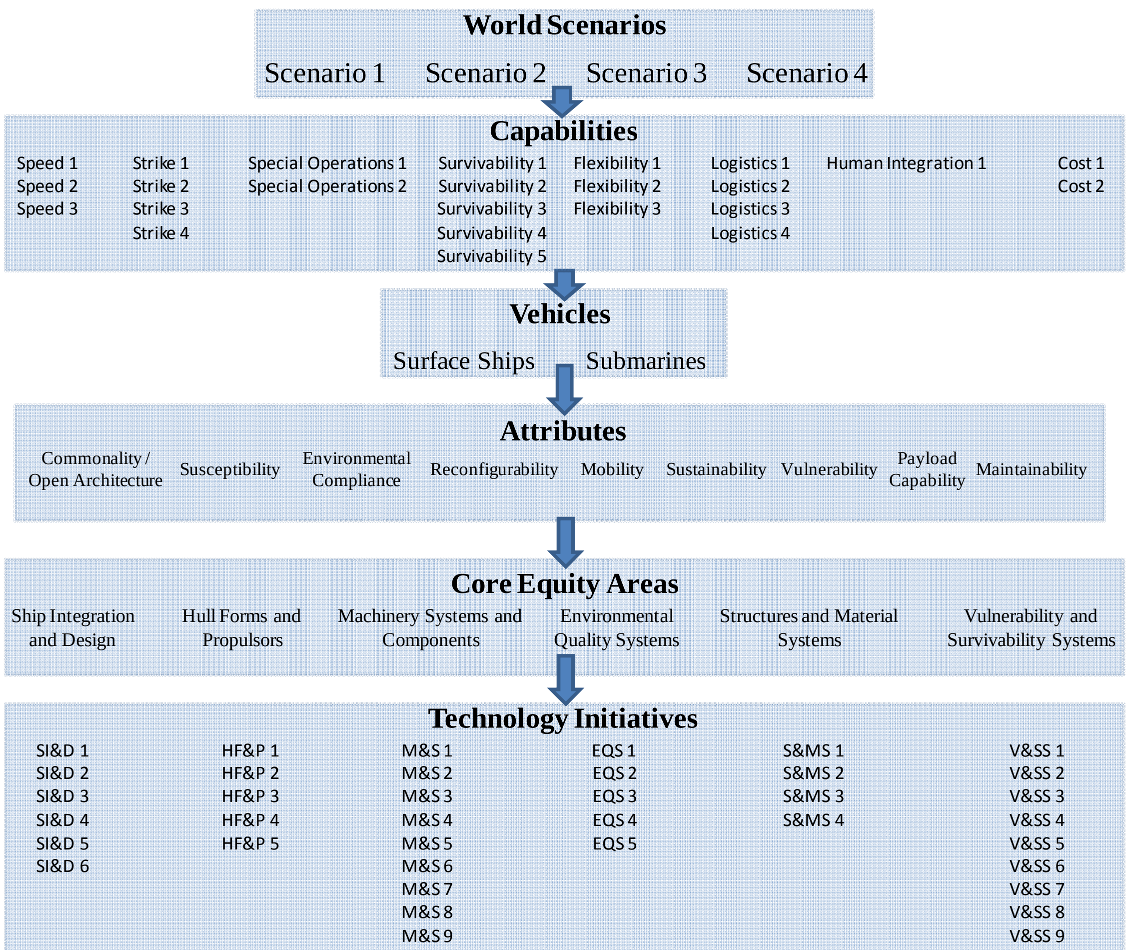


Figure 25: Naval Application Hierarchy

Step 3: Prioritize the Goals

The relative prioritization of the goals to the world scenarios was performed during a workshop attended by several high ranking members of NAVSEA and ONR. The goal was to be briefed on the scenarios, how they affected the Navy, and then to vote on the priorities of the goals to the world scenarios. These values were arrived at during a workshop voting situation where all the members were present and the scenarios were explained. The scenario discussion reduced the total list of capabilities to those which the group felt has some degree of applicability to the defined scenarios. Following this determination the voting was performed.

For the four world scenarios, between ten and eleven were determined to be applicable. Attempting to perform this voting by the pairwise comparison method would result in 220 total votes by the workshop participants. In contrast a cumulative voting method only requires determining the values for 44 prioritizations. This difference and constraints placed on the duration of the workshops led to the decision to utilize the cumulative voting for this prioritization.

In order to determine the number of samples required, Equation 4 was utilized with assumptions of the alpha value set at 0.05 and a margin of error of 5%. This margin of error was chosen because on the 10 point scale the sample mean could have been in error by ½ a point to either direction which was determined to be acceptable. The standard deviation is estimated by dividing the scale of the voting, 10, by the spread which will cover almost all of the points, 8. From this calculation the sample size should be 17 votes. Based on the actual voting distribution and corresponding standard deviations the number of calculated sample sizes are shown in Figure 26. Of the 41 different votes, 18 come in under or on the number actually taken while 23 exceed it. This was caused by the standard deviation of the actual samples exceeding the estimated value by a large margin. Of particular note is that both Scenario 3 and Scenario 4 showed particularly large standard deviations.

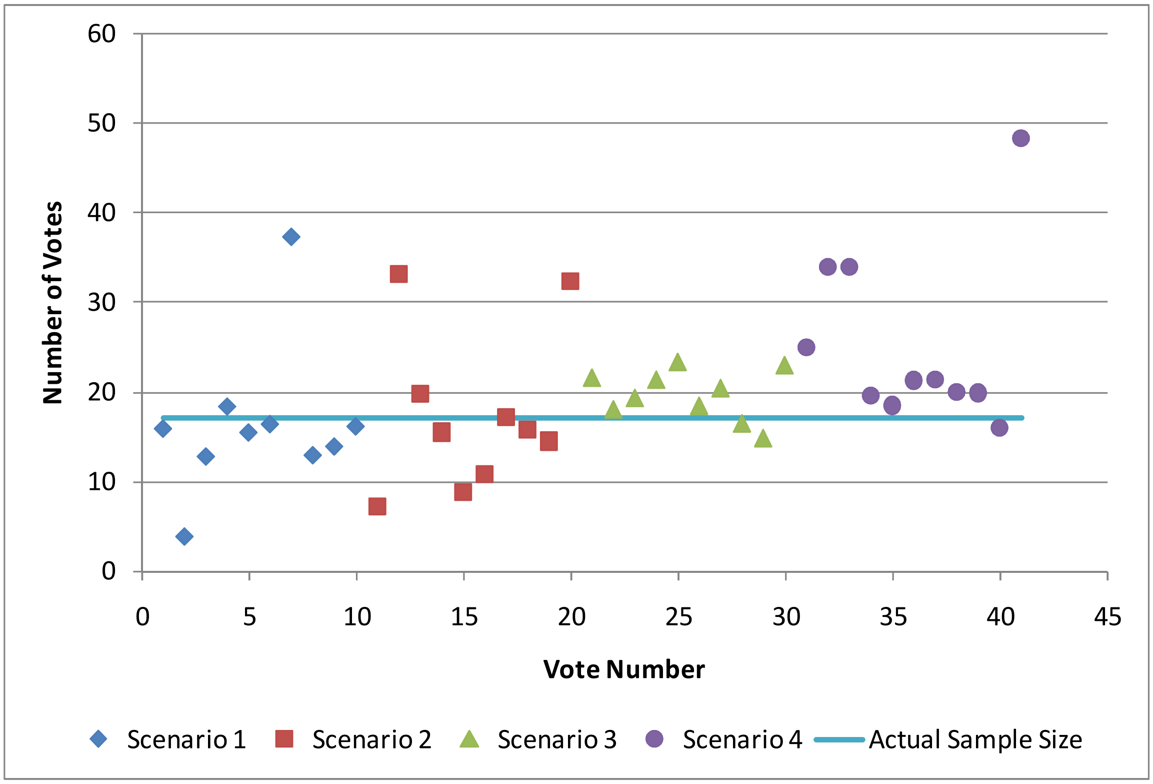


Figure 26: Capability Importance Sample Size Evaluation

Voting was performed utilizing an ordinal ranking scheme where each member was asked to place the capabilities in order by their importance to the specified scenario. The median values of the capabilities were computed and normalized by the maximum value for each of the scenarios. The resulting values are listed in Table 10. Survivability 4 is the most important capability for Scenario 1 and one of the two most important for Scenario 2 along with Speed 3. For Scenario 3 Speed 1 and Flexibility 1 are the most important, and Human Integration 1 is the most important for Scenario 4.

Table 10: Capability Importance Values for Navy World Scenarios

Scenario 1		Scenario 2		Scenario 3		Scenario 4	
Capability	**Importance**	**Capability**	**Importance**	**Capability**	**Importance**	**Capability**	**Importance**
Speed 2	93	Speed 3	100	Speed 1	100	Strike 1	78
Strike 1	80	Strike 1	56	Strike 1	63	Strike 2	67
Strike 2	80	Strike 3	69	Strike 3	75	Special Operations 2	44
Survivability 1	93	Strike 4	63	Special Operations 1	69	Survivability 3	72
Survivability 2	87	Survivability 2	25	Survivability 2	50	Survivability 4	78
Survivability 3	33	Survivability 3	56	Survivability 3	50	Flexibility 2	28
Survivability 4	100	Survivability 4	100	Survivability 5	25	Logistics 3	78
Survivability 5	27	Flexibility 3	25	Flexibility 1	100	Logistics 4	44
Logistics 2	53	Logistics 2	88	Logistics 1	81	Human Integration 1	100
Cost 1	67	Cost 1	94	Logistics 3	69	Cost 1	50
Cost 2	67	Cost 2	94			Cost 2	50

Each scenario represented a specific world engagement in which the Navy could be involved. It is also possible for all of the scenarios to be compiled into a single list of importances. If the decision makers believe that the scenarios have different probabilities of occurrence, this could be used as weighting factors; however, for this application, each was equally probable. The median of each capability was summed across the scenarios and normalized based on the maximum value. The resulting list is given in Table 11. Strike 1 and Survivability 4 are the most important capabilities with the groups of strike and survivability being the greatest overall.

Table 11: Compiled Capability Importance Values Across Scenarios

Capability	Importance
Speed 1	36
Speed 2	31
Speed 3	36
Strike 1	100
Strike 2	53
Strike 3	51
Strike 4	22
Special Operations 1	24
Special Operations 2	18
Survivability 1	31
Survivability 2	56
Survivability 3	78
Survivability 4	100
Survivability 5	18
Flexibility 1	36
Flexibility 2	11
Flexibility 3	9
Logistics 1	29
Logistics 2	49
Logistics 3	56
Logistics 4	18
Human Integration 1	40
Cost 1	76
Cost 2	76

Cumulative Voting Demonstration

The use of the rank order scheme for the NAVSEA application was based on opinion of a senior member of the management of the program and is deficient for prioritization for the reasons specified in Chapter 3. The cumulative voting technique which is stipulated in Hypothesis 1 was previously demonstrated in a pilot study for the Navy performed in April of 2006. In this study the top level goals were identified as a set of Naval Needs which were to ranked based on their importance to two potential timeframes, 2015 and 2030.

The prioritization was performed at a workshop where the Naval Needs were defined and discussed. The 25 participants then were given two 5-point chips, three 3-point chips, and five 1-point chips to distribute amongst the 10 Needs as they saw fit. This denomination was decided such that it was possible to give every need at least 1 chip to show it had some importance. The points were then summed and the total importance rankings for the Naval Needs determined. These results are shown in Table 12.

Table 12: Naval Needs Rankings for Cumulative Voting Example

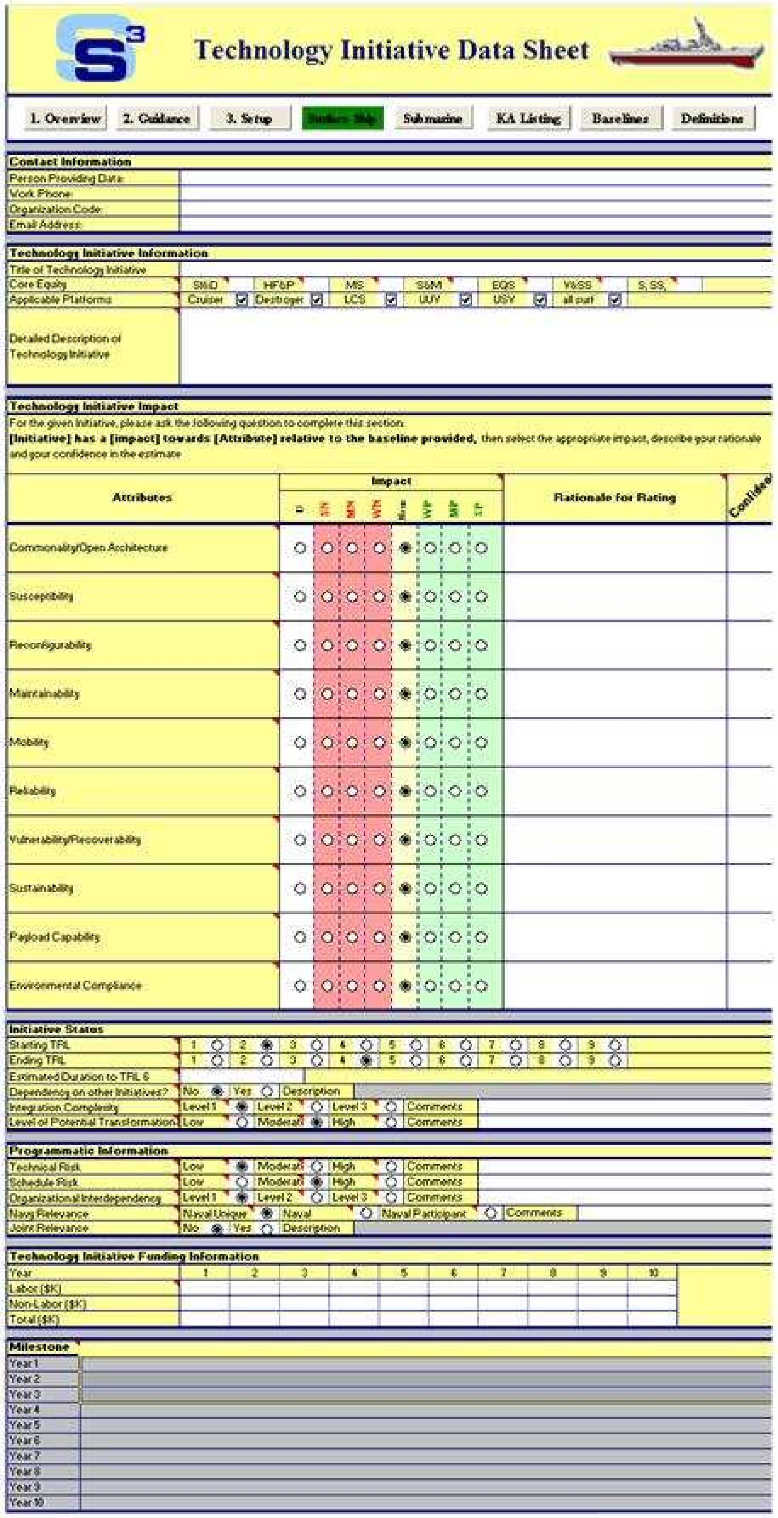
	2015			2030		
	Weighted sum	Normalized	Rank	Weighted sum	Normalized	Rank
Joint Littoral Operations	68	87	3	49	55	7
Sustained Forward Presence	55	71	8	48	54	8
Interoperability	69	88	2	60	67	5
Battlespace Dominance	68	87	4	87	98	2
Power Projection	48	62	10	65	73	4
Joint Focused Logistics & Sustainment	65	83	5	70	79	3
Optimized Manning	62	79	6	48	54	9
Protection in Asymmetric Threat Environment	50	64	9	48	54	10
Force Flexibility	60	77	7	89	100	1
Affordability	78	100	1	56	63	6

Step 4: Gather Program Information

Secondary Information

The decomposition hierarchy created the levels of the problem from the organization goals down to the system level attributes. The next step was to obtain the information on the programs which would be prioritized. For this application the Core Equity Area mangers were given a questionnaire to be filled out by their technologists that pulled information based on the attributes and capabilities specified. The questionnaire is shown in Figure 27.

The “Contact Information” section was for capturing information about the program manager most involved with the technology. Recording this information allowed for those overseeing the process to quickly get corrections and clarification to information which was entered on the sheet that was not clear. Also, this information allows for accountability and traceability in the final plan with a direct link to those technologists which were involved and the number and quality of proposed programs.


Technology Initiative Data Sheet

1. Overview | 2. Guidance | 3. Setup | Surface Ship | Submarine | KA Listing | Baselines | Definitions

Contact Information

Person Providing Data:	
Work Phone:	
Organization Code:	
Email Address:	

Technology Initiative Information

Title of Technology Initiative							
Core Equity	S&D	HF&P	MS	S&M	EQS	V&SS	S, SS,
Applicable Platforms	Cruiser ☑	Destroyer ☑	LCS ☑	UUV ☑	USV ☑	all surf ☑	
Detailed Description of Technology Initiative							

Technology Initiative Impact

For the given Initiative, please ask the following question to complete this section:
[Initiative] has a [impact] towards [Attribute] relative to the baseline provided, then select the appropriate impact, describe your rationale and your confidence in the estimate

Attributes	Impact	Rationale for Rating	Confidence
Commonality/Open Architecture			
Susceptibility			
Reconfigurability			
Maintainability			
Mobility			
Reliability			
Vulnerability/Recoverability			
Sustainability			
Payload Capability			
Environmental Compliance			

Initiative Status

Starting TRL	1	2	3	4	5	6	7	8	9
Ending TRL	1	2	3	4	5	6	7	8	9
Estimated Duration to TRL 6									
Dependency on other Initiatives?	No	Yes	Description						
Integration Complexity	Level 1	Level 2	Level 3	Comments					
Level of Potential Transformation	Low	Moderate	High	Comments					

Programmatic Information

Technical Risk	Low	Moderate	High	Comments
Schedule Risk	Low	Moderate	High	Comments
Organizational Interdependency	Level 1	Level 2	Level 3	Comments
Navy Relevance	Naval Unique	Naval	Naval Participant	Comments
Joint Relevance	No	Yes	Description	

Technology Initiative Funding Information

Year	1	2	3	4	5	6	7	8	9	10
Labor ($K)										
Non-Labor ($K)										
Total ($K)										

Milestone

Year 1	
Year 2	
Year 3	
Year 4	
Year 5	
Year 6	
Year 7	
Year 8	
Year 9	
Year 10	

Figure 27: Program Information Sheet Questionnaire

The "Technology Initiative Information" recorded the name, description and category of the program. Also, the applicable program to which the technology could be applied was also recorded. This piece of information allowed the final decision makers to judge the impacts that technology would have not just on a vague "system" but on the fleet of the future. A program which affected only one ship type might not have the overall impact that one which affected all types would.

The "Technology Initiative Impact" section was designed in order to allow the technologists to express their opinion as to their programs impact on the system attributes. Since these managers have a large stake in their programs being funded for the future the bias here was large enough that it was not possible to include these values as votes in the final tally. However, capturing other information from the technologists is made easier if there is a belief that information was being collected overall.

"Initiative Status" is where information relating to what level of maturity the technology had achieved. Maturity was measured in terms of the Technology Readiness Levels (TRL) which is a measure created by NASA and is shown in Table 13 (National Resource Council 1998). This section also captured the duration until the final TRL is reached as well as two different measures of the how the time can be leveraged to perform the research. The first such measure is the "Integration Complexity" which measures how difficult it is for the final technology product to be integrated into a larger system. The definition for each of the complexity levels is given in Table 14.

Table 13: Technology Readiness Levels

Technology Readiness Level	Description
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function or characteristic proof-of-concept or completed design
4	Component and/ or application formulated
5	Component verification in a relevant environment
6	System/ subsystem model or prototype demonstrated/ validated in a relevant environment
7	System prototype demonstrated in flight
8	Actual system completed and "flight qualified" through test and demonstration
9	Actual system "flight proven" in operational flight

Table 14: Integration Complexity Definitions

	Detailed Descriptions
Level 1	Application of this Technology Initiative will require only minor modifications to interfacing or supporting naval components/systems.
Level 2	Application of this Technology Initiative will require moderate modifications to interfacing or supporting naval components/systems.
Level 3	Application of this Technology Initiative will require significant modifications to interfacing or supporting naval components/systems.

"Programmatic Information" is information having to do with the research of the technology rather than the outcome itself. Technical Risk is the probability that the research will not be completed or that will suffer technical setbacks limiting their performance of the final product. Schedule risk is the probability that the specified durations and timelines will slip or not be met. The Organizational Interdependency is the degree to which the research is conducted within the Navy and definitions for the levels are given in Table 15. Navy Relevance is a measure of the application of the results of the program to organizations other than the Navy and the definitions of its levels are given in Table 16.

Table 15: Organizational Interdependency Definitions

Organizational Interdependency	Detailed Descriptions
Level 1	The technical capabilities needed to perform this Technology Initiative are resident within a single technical discipline within a Navy activity (including its affiliated university/industry partners).
Level 2	The technical capabilities needed to perform this Technology Initiative require the active participation of more than one technical discipline within a single Navy activity (including its affiliated university/industry partners).
Level 3	The technical capabilities needed to perform this Technology Initiative require the active participation of more than one Naval activity (including its affiliated university/industry partners).

Table 16: Navy Relevance Definitions

Navy Relevance	Detailed Descriptions
Naval Unique	Technology needed exclusively for naval applications: no one else will develop.
Naval Harvest	Technology that has applicability to both naval and non-naval applications which offers investment leveraging opportunity; others are investing in the technology.
Naval Participant	Potential transformational technology that the naval community should keep abreast of through limited investment.

"Technology Initiative Funding Information" is the section where the funding profiles are entered. Here the technologists specify the amount of money that they believe the project will require over the next 10 years. The amount is divided into how much goes into labor and how much is non-labor. It should also be noted that the amount is given in terms of how much funding is needed per year of research and not per Fiscal or calendar year. The difference being that with this notation the program can be moved to later years if resources are not immediately available.

The final "Milestone" section relates notable transitions and stages of the research. This information will allow the planners to gauge how well the work is progressing and when new capabilities will come online. This section is also useful in the context of enabling technologies, as it could show at what point a concept has reached enough maturity to allow another technology to begin development.

This technology data sheet was pretested amongst several technologists to capture their feedback on its design and feasibility. Their comments led to a greater expansion of the definitions of the various terms to ensure that everyone fully understood their meanings. When submitted to the Core Equity leaders a total of 61 technologies were submitted.

Technology Interrelationships

The three types of interrelationships; compatibility, enabling, and synergistic all existed in this application and needed to be captured by the planners. The first interrelationship, incompatibility, is shown in Table 17 where a "1" represents a compatible combination and a "0" an incompatible one. The matrix is symmetric along the diagonal as no order is placed on one technology causing the other to be excluded, but, rather, it is the combination of the two which gives this result.

Table 17: Surface Ship Technology Incompatibility Matrix

	SI&D 1	SI&D 2	SI&D 3	SI&D 4	SI&D 5	SI&D 6	HF&P 1	HF&P 2	HF&P 3	HF&P 4	HF&P 5	M&S 1	M&S 2	M&S 3	M&S 4	M&S 5	M&S 6	M&S 7	M&S 8	M&S 9	S&M 1	S&M 2	S&M 3	S&M 4	EQS 1	EQS 2	EQS 3	EQS 4	EQS 5	V&SS 1	V&SS 2	V&SS 3	V&SS 4	V&SS 5	V&SS 6	V&SS 7	V&SS 8	V&SS 9
SI&D 1		1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1
SI&D 2	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
SI&D 3	1	1		1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
SI&D 4	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1
SI&D 5	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
SI&D 6	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
HF&P 1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
HF&P 2	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
HF&P 3	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
HF&P 4	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
HF&P 5	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
M&S 1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
M&S 2	1	1	1	1	1	1	1	1	1	1	1	1		1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
M&S 3	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
M&S 4	0	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
M&S 5	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1		1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1
M&S 6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1
M&S 7	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
M&S 8	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
M&S 9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S&M 1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
S&M 2	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S&M 3	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
S&M 4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1
EQS 1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1
EQS 2	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	0	1	1	1	1	1	1
EQS 3	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1
EQS 4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1
EQS 5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1
V&SS 1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1
V&SS 2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1
V&SS 3	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1		1	1	1	1	1	1
V&SS 4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1		1	1	1	1	1
V&SS 5	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1
V&SS 6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1
V&SS 7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1
V&SS 8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1
V&SS 9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	

The enabling technology matrix is given in Table 18 where a “1” represents an enabling combination. This matrix is not symmetric, however, owing to the fact that one program enables the other, but the reverse sentiment is not true. In this representation the technology which does the enabling is given in a row, and the corresponding column is the enabled technology.

Table 18: Surface Ship Enabling Technology Matrix

	SI&D 1	SI&D 2	SI&D 3	SI&D 4	SI&D 5	SI&D 6	HF&P 1	HF&P 2	HF&P 3	HF&P 4	HF&P 5	M&S 1	M&S 2	M&S 3	M&S 4	M&S 5	M&S 6	M&S 7	M&S 8	M&S 9	S&M 1	S&M 2	S&M 3	S&M 4	EQS 1	EQS 2	EQS 3	EQS 4	EQS 5	V&SS 1	V&SS 2	V&SS 3	V&SS 4	V&SS 5	V&SS 6	V&SS 7	V&SS 8	V&SS 9
SI&D 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SI&D 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SI&D 3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SI&D 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SI&D 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SI&D 6	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF&P 1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF&P 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF&P 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0
HF&P 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF&P 5	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M&S 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M&S 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M&S 3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
M&S 4	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M&S 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
M&S 6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M&S 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M&S 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M&S 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
S&M 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S&M 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S&M 3	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S&M 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
EQS 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EQS 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EQS 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
EQS 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EQS 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V&SS 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V&SS 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
V&SS 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V&SS 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V&SS 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
V&SS 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V&SS 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V&SS 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V&SS 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

Synergism is the ability of a program combination to have greater or less benefit than just the sum of their individual contributions. The Naval synergism, shown in Table

19, has both increases in the overall contribution as well as some small decreases. These degradations could be due to the inability of two programs to get their full benefits because they are sharing assets or expert personnel are being shared between them when they would have a greater benefit as a full time employee to just one. It should be noted that the “0’s” in the matrix represent incompatible technologies.

Table 19: Surface Ship Technology Synergism Matrix

	SI&D 1	SI&D 2	SI&D 3	SI&D 4	SI&D 5	SI&D 6	HF&P 1	HF&P 2	HF&P 3	HF&P 4	HF&P 5	M&S 1	M&S 2	M&S 3	M&S 4	M&S 5	M&S 6	M&S 7	M&S 8	M&S 9	S&M 1	S&M 2	S&M 3	S&M 4	EQS 1	EQS 2	EQS 3	EQS 4	EQS 5	V&SS 1	V&SS 2	V&SS 3	V&SS 4	V&SS 5	V&SS 6	V&SS 7	V&SS 8	V&SS 9
SI&D 1	1.00	1.00		1.00		1.00		1.00		1.00		1.00		1.00	0.00	1.00		1.00		1.00		1.00		1.00		1.00		1.00		0.00	1.25	1.00		1.00		1.00		1.00
SI&D 2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.03	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SI&D 3		1.00	1.00	1.00		1.00		1.00		1.00		1.00		1.00		0.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00
SI&D 4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	1.00	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00
SI&D 5		1.00		1.00	1.00	1.00		1.00		1.28		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.08
SI&D 6	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.16	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
HF&P 1		1.00		1.00		1.00	1.00	1.00		1.00		1.00		1.00		1.00		1.00	0.00	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00
HF&P 2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
HF&P 3		1.00		1.00		1.00		1.00	1.00	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00
HF&P 4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.26	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
HF&P 5		1.00		1.00		1.00		1.00		1.00	1.00	1.00		1.00		1.00		1.00	1.12	1.00		1.00	0.00	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00
M&S 1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
M&S 2		1.00		1.00		1.00		1.00		1.00		1.00	1.00	1.00		0.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		0.00		1.00		1.00		1.00
M&S 3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
M&S 4	0.00	1.00		1.00		1.00		1.00		1.00		1.00		1.00	1.00	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00
M&S 5	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
M&S 6		1.00		1.00		1.00		1.00		1.00		1.17		1.00		1.00	1.00	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		0.00		1.00
M&S 7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.08	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00
M&S 8	1.01	1.00		1.00		1.00	0.00	1.00		1.00		1.00		1.00		1.00		1.00	1.00	1.00		1.00		1.00		1.00		0.00		1.00		1.00		1.00		1.00		1.00
M&S 9	1.00	1.00	1.19	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.28	1.00
S&M 1		1.00		1.00		1.00		1.00		1.00		1.00		1.00		0.00		1.36		1.00	1.00	1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		0.00
S&M 2	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
S&M 3		1.00		1.00		1.00		1.00		1.00	0.00	1.00		1.00		1.00		1.00		1.00		1.00	1.00	1.00		1.00		1.00		1.00		1.00	0.00	1.00		1.00		1.00
S&M 4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.26	1.00	1.00	1.00	1.00	1.00	1.00
EQS 1		1.00		1.00		1.00		1.00		1.00		1.00	1.28	1.00		1.00		1.00		1.00		1.00		1.00	1.00	1.00		1.00		1.00		1.00		1.00		1.00		1.00
EQS 2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.20	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
EQS 3		1.00		0.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	1.00	1.00		1.00		1.00		1.00		1.00		1.00
EQS 4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
EQS 5		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	1.00	1.00		1.00		1.00		1.00		1.00
V&SS 1	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
V&SS 2		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	1.00	1.00		1.00		1.00		1.00
V&SS 3	1.00	1.00	1.00	1.00	1.36	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
V&SS 4		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	0.00	1.00		1.00		1.00		1.00		1.00	1.00	1.00		1.00		1.00
V&SS 5	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
V&SS 6		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00	1.00	1.00		1.00
V&SS 7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
V&SS 8		1.00		1.00		1.00		1.00		1.00		1.00		1.00		1.00		0.00		1.00		1.00		1.00	1.29	1.00		1.00		1.00		1.00		1.00		1.00	1.00	1.00
V&SS 9	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.94	1.00	1.00	1.36	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Step 5: Assess Hierarchy Relationships

After the information was captured on the technologies, two workshops were scheduled, one for surface ships and one for submarines. Separate meetings were held because the Navy had different sets of Subject Matter Experts for each of the vehicle types. The participants included management of the group putting together the Science and Technology plan as well as system level experts and the head of each of the Core Equity Areas. The location of the workshop was a large conference room with multiple projectors for displaying technology information and the voting data, which was located at the same facility as the majority of the individuals taking part in the workshop.

Workshop Facilitation

The format for both workshops was identical and started with a briefing on the definitions of the attributes and capabilities. In addition to identifying what each term meant, a particular emphasis was placed on explaining the direction of improvement which would be a "benefit" to the organization. This clarification was intended to head off misunderstandings in the voting as to what constitutes a "positive" or "negative" vote. Following the briefing, a discussion was held to ensure that the attributes identified were believed appropriate to capture the technology impacts to the higher level capabilities.

Following the definitions briefing, the voting between the system level attributes and the capabilities was performed. This was accomplished through the use of a commercial Personal Response System (PRS™) which utilizes a handheld infrared transmitter and a receiver attached to a computer running vote collection software. The handheld device consists of 10 numerical buttons and two confidence buttons which can be used to differentiate between opinions which are held strongly and those which are not. For the attribute to capabilities mapping the numerical scale for the relationships was a 1-7 which is shown in Table 20.

Table 20: Voting Scale for Naval Workshops

Descriptor	Numerical Value
Strong Negative	1
Moderate Negative	2
Weak Negative	3
No Impact	4
Weak Positive	5
Moderate Positive	6
Strong Positive	7

Following the attribute to capability voting, the technology to attribute voting was performed. For each technology the head of the corresponding Core Equity would give a presentation based on a standardized template to describe what exactly was involved in the program, and how it was accomplished. The template was created in order to restrict the amount of time devoted to the discussion of each technology as well as to keep the descriptions at the same level of detail. Bias can be introduced into the system if one program is given a more or less in-depth briefing than all the others. After describing the technology, a small discussion is held to clarify any misunderstandings, and then the vote is performed.

Voting Sample Size

Determining the appropriate number of voters to employ is a balance between the number statistically required and the amount who can be gathered together easily and affordably. In order to compute a good sample size the following equation is used:

$$n_0 = \frac{(t^2)(s^2)}{d^2}$$

The value (t) for the alpha level of 0.1 is equal to 1.65. The acceptable margin of error (d) is the percent error times the scale of the voting. For this application the percent error of 7% was utilized with the 7 level scale to get a margin of 0.49. This means that the true mean of the distribution can be up to 0.49 different from the actual mean. Since the calculations used focus on the median, this difference is insufficient to cause an unacceptable change between the voted upon impact and the true impact. Estimating the standard deviation (s) can be accomplished by dividing the number of standard deviations encompassing 98% of the responses (6) by the number of values possible (7) which gives a result of (1.167). The resulting number of votes which are needed for an appropriate sample is 15.

Originally 15 to 20 people were asked to participate in the workshops; however due to schedule conflicts, only 12 were able to attend the surface ship workshop but all 15 were present for the submarine one. As the day wore on the number of participants who were actually voting varied as people left the room to attend to cell phone calls or email. Upon completing the vote it was possible to analyze the resulting sample statistics and to calculate whether the size was sufficient to be within the desired margin of error of 7%. This was accomplished by utilizing the equation above and substituting the actual standard deviation of the sample for the estimated. The plotted values for the number of votes taken and the number required based on the standard deviation are shown in Figure 28. Over the workshop there 112 of the 726 votes or 15% required more samples than were taken. This difference can be remedied either by revoting the impacts which result in large standard deviations or by soliciting more votes from other personnel to bring the value closer to that required to bring the margin of error within satisfactory bounds. If this second option is chosen the number of new samples to be acquired is chosen by subtracting the number of votes which were actually taken from the sample size required based off the standard deviation of the distribution.

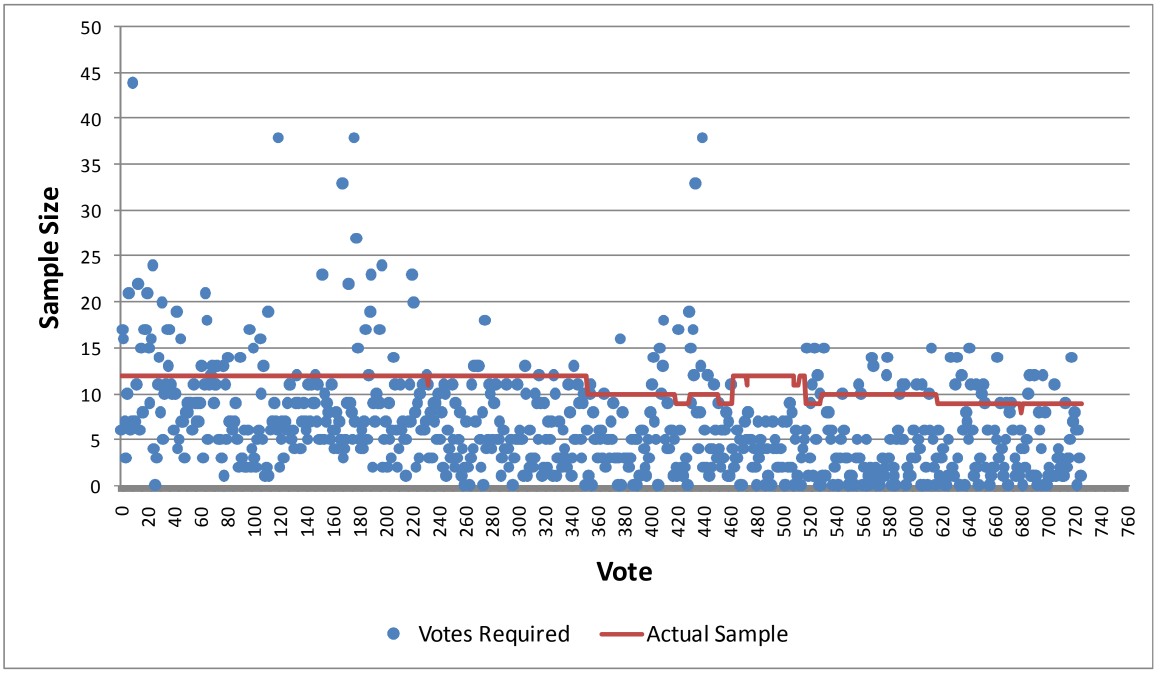


Figure 28: Sample Sizes of Surface Ship Workshop

For the second technology impact workshop, which focused on the submarine, the number of voters was greater than for the first technology workshop, which focused on surface ships. This was due in part to the workshop being held on a better date for gathering people together as well as an increased visibility of the methodology following the first voting session. This voting session started with 13 individuals, but that number climbed to 15 at one point before settling around 14. The number of voters and the number of required votes based on the standard deviation are given in Figure 29. This workshop proved to have a much smaller standard deviation across the technologies, which is evident in that only 4 of the 341 votes, or 1%, required more samples than the number used.

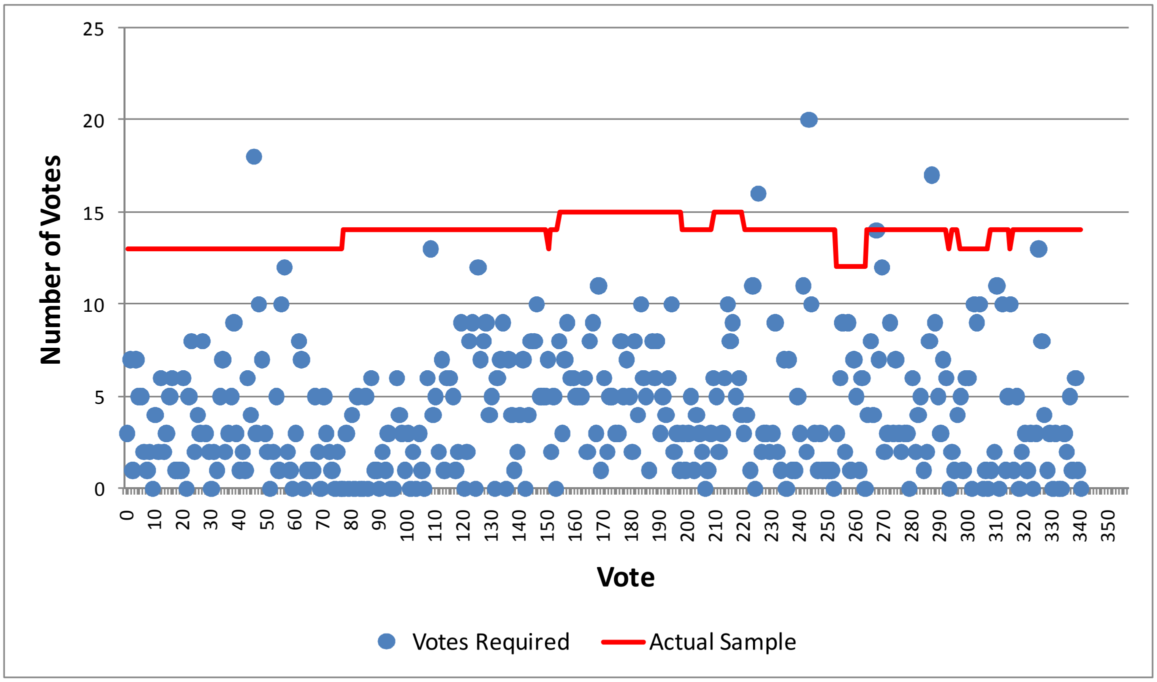


Figure 29: Sample Sizes for Submarine Workshop

Voting Statistics

Following the workshop it was necessary to analyze the votes to determine whether any irregularities existed that needed to be addressed or corrected. This was performed first by estimating the shape parameters of the beta distribution and analyzing the results to look for indicators of bimodal or uniform distributions. After performing the analysis it was found that none of the votes took a bimodal distribution, but some did behave uniformly such as the relationships between S&M 3 and Environmental Compliance shown in Figure 30. For such a vote there was a clarification needed, and a final decision was to assign this relationship a value of No Impact due to all the votes being based on secondary impacts rather than primary ones. The other two types of voting distributions are the normal and exponentially increasing which are both acceptable and the median utilized as computed.

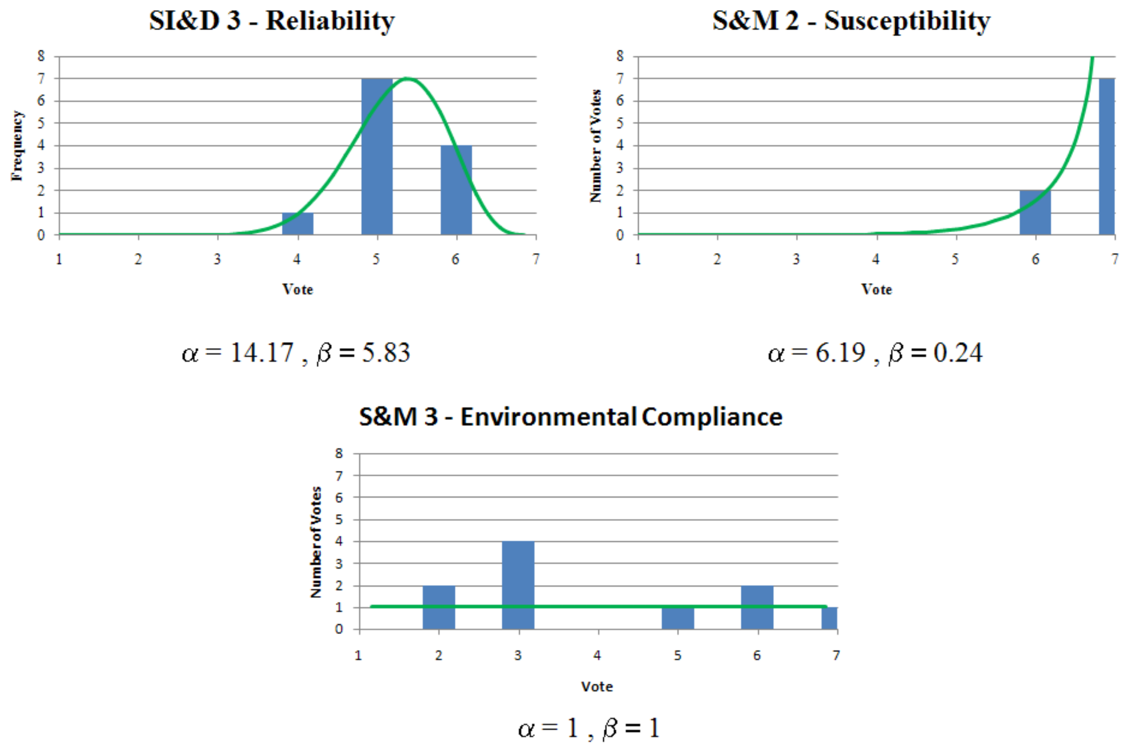


Figure 30: Sample Surface Ship Vote Distributions

Other statistical analyses were performed to see what patterns were present in the voting results which could better inform future workshops. One such analysis was to plot the average standard deviation of the votes across the attributes, capabilities, or technologies. This allowed the facilitator to see whether a particular attribute or technology shows a greater disparity than the others as this could illustrate a poor definition or overly broad category. For the standard deviation of the attributes across the technologies, shown in Figure 31, the values turned out to be fairly close with the only true outlier being Environmental Compliance. This can be easily explained as all but four of the nine technologies which mapped to this attribute were from the Environmental Quality Systems Core Equity Area, which was a particularly easy judgment for the voting participants to make. In examining how the votes vary amongst the technologies, shown in Figure 32, there are two Core Equities which show less than average variance, Environmental Compliance and Vulnerability Systems. This could be due to both of these groups having attributes which are directly related to these technologies which can over simplify the job of the workshop participants in assigning their own relationships. Whether the Core Equity name adds bias to the vote is indeterminable, but if a group felt that it was an issue the technologies could be presented in such a way as to not categorize them and utilize purely the description.

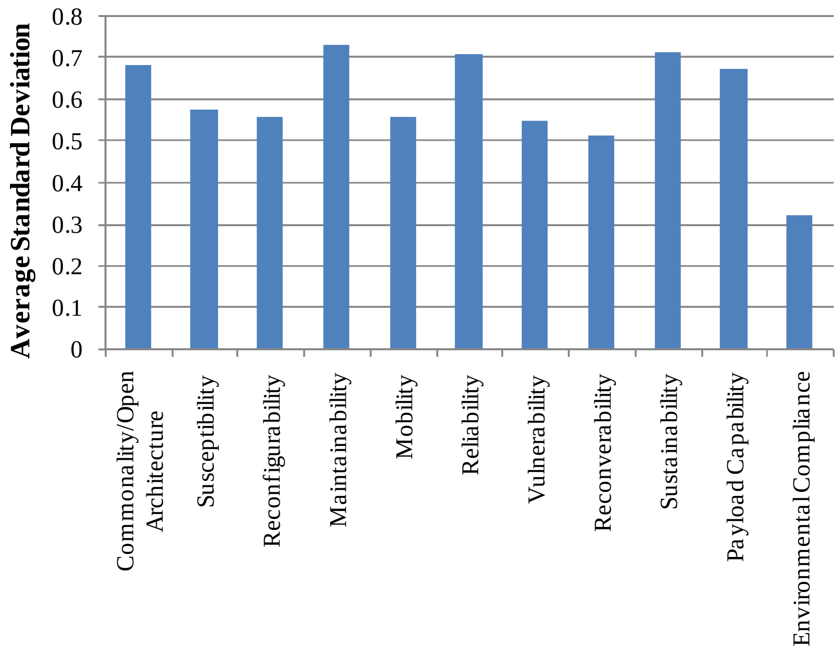


Figure 31: Standard Deviation of Attributes Across All Surface Ship Technologies

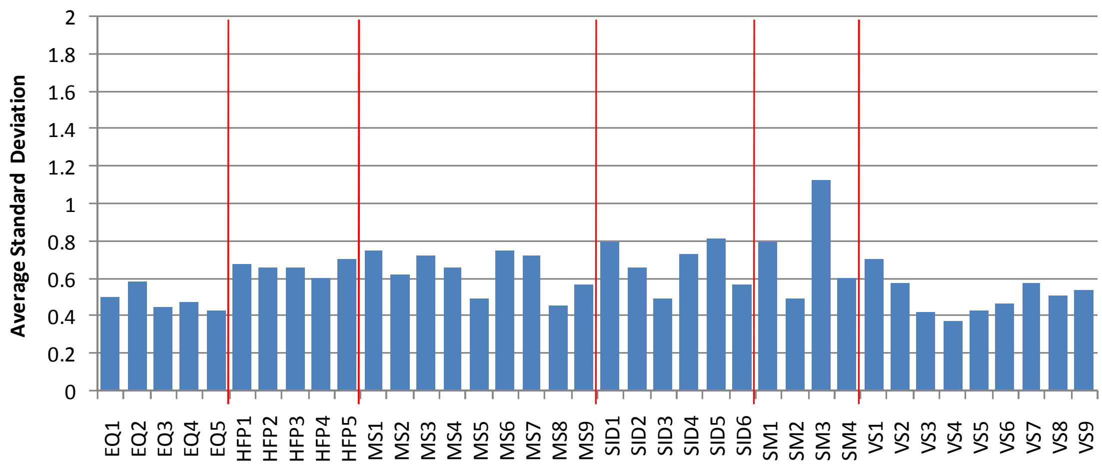


Figure 32: Standard Deviation for Surface Ship Technologies across All Attributes

The relationships determined by the Subject Matter Experts are illustrated in Figure 33 and shows several notable trends. The lack of any impacts to the capabilities of Strike 3, Strike 4, and Special Operations 1 is due to the fact that these are only applicable to submarine application so no relationships were created in the surface ship workshop. The Cost1 capability which has to do with the acquisition cost of a system is negatively affected by nearly every attribute except Commonality/Open Architecture which positively benefits it. This is a logical relationship since the increase in the ability of a system to be used across multiple platforms will decrease the integration and manufacturing costs associated with it. Survivability 2 is only affected by Susceptibility which indicates that only technologies able to influence this attribute will be beneficial for the capability.

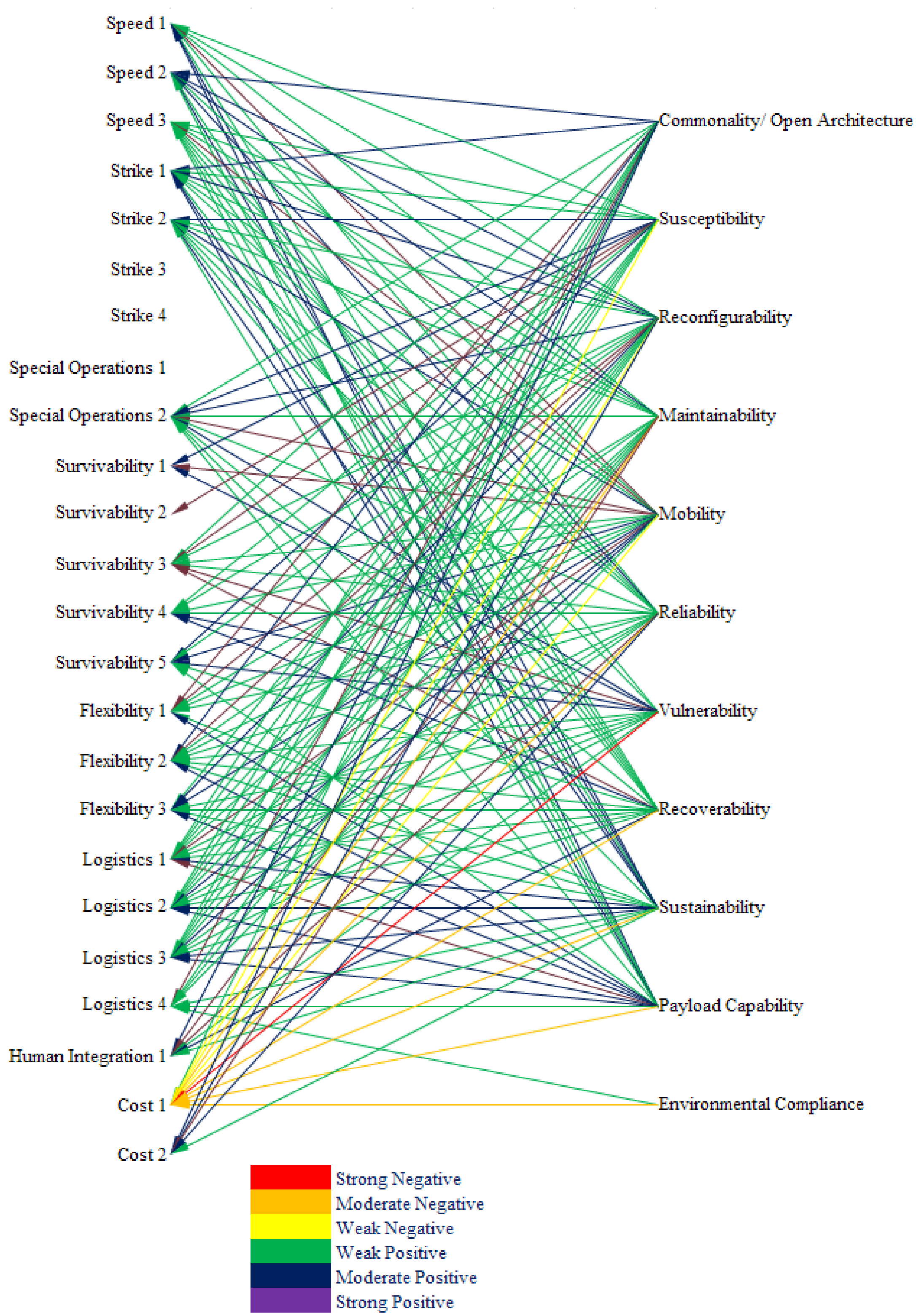


Figure 33: Surface Ship Attribute to Capability Relationships

The second voting session in each workshop focuses on the impacts of the technologies to the system level attributes. A briefer, designated by each Core Equity would present basic information on the project and answer questions raised by the other participants, and then voting would be performed. The quantitative scale used was also a 7 level scale from Strong Positive to Strong Negative. The relationships are shown in Figure 34.

The relationships between the technologies and attributes showed a very positive nature with only 3 programs having negative mappings. This could be the true trend, or it could be due to the vagueness of the descriptions of the attributes or the programs themselves. The less mature a technology is, the less information is available as to its application and final impact. This can lead the vote to reflect the improvement which is being specifically aimed for without accounting for the as yet unknown costs which may accompany it.

The majority of all the relationships are weak in nature, but there does exist three distinct groups which contribute strongly to the attributes. These include Environmental Quality System technologies which influence the attribute Environmental Quality, Vulnerability and Survivability Systems which influence Vulnerability, and Hull Form and Propulsors which contribute to Mobility. Because the technologies which are placed in each of those groups are specifically meant to address the corresponding attributes, these relationships make logical sense.

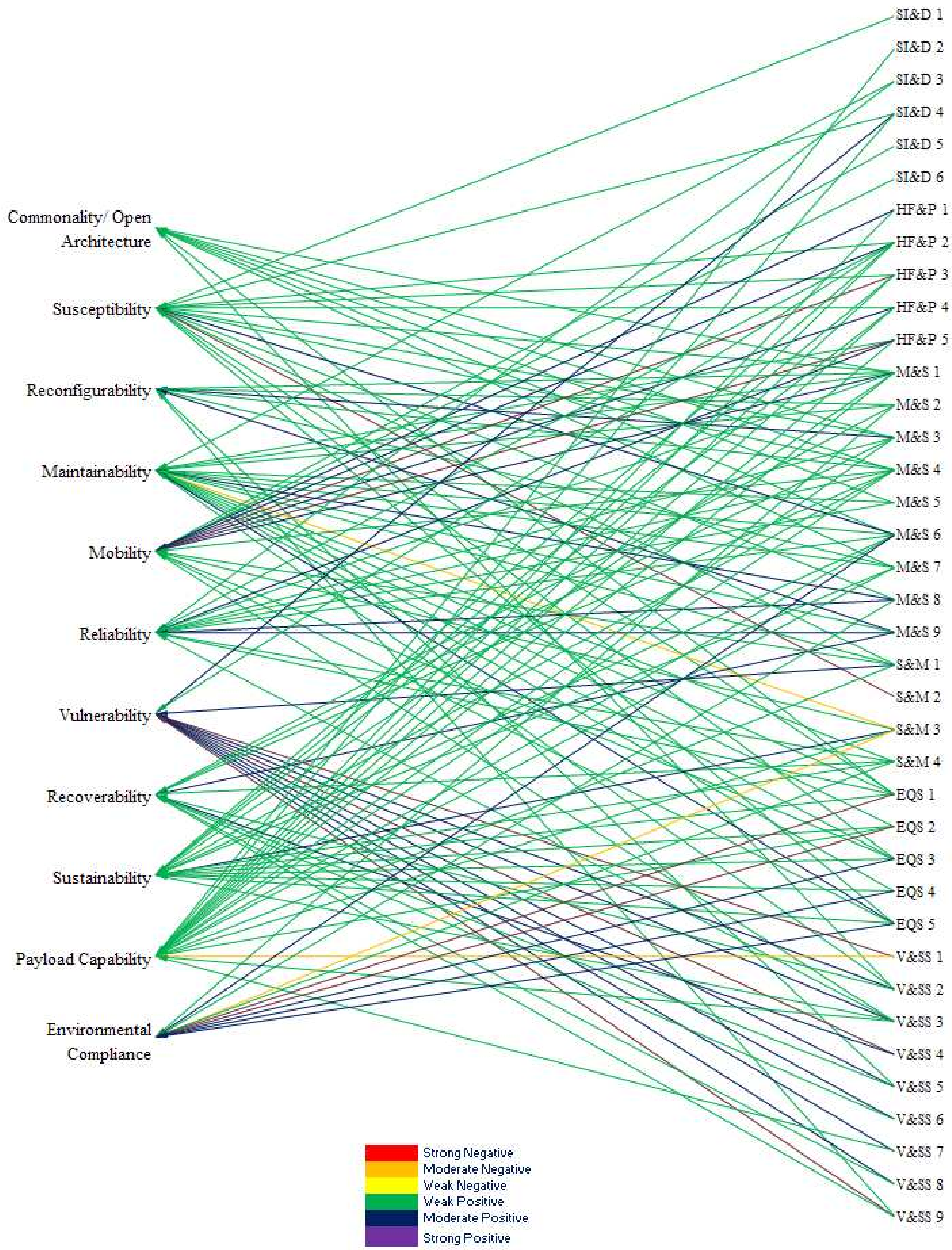


Figure 34: Relationships between Surface Ship Technologies and Attributes

Step 6: Program Evaluation

Because a single technology will not accomplish all the capabilities required by the Navy of the future, it is necessary to develop a solid portfolio. Because each collection has unique attributes, the decision maker must ultimately choose the one which gives the greatest benefit for the available resources. Since there are relationships between the various technologies, the best portfolio may not have been the collection of the highest ranked technologies but, rather, a combination which takes these into account.

Technology Benefit Score

In order to properly evaluate the portfolio of concepts, it is necessary to have a measure of the impact of the each of the technologies to the system level capabilities. This was accomplished in this application by first taking the votes on the impacts of the technologies, attributes and capabilities and converting them to a nonlinear scale. This scale is given in Table 21. Values of one are given in both scales for the Weak descriptors due to the tendency of voters to give these relationships when they feel that some impact is warranted but not enough to make much a of an overall impact on the system. The only difference in the two scales is the value for the Moderate descriptor which is 5 and -5 for the technologies to attributes and 7 and -7 for the attributes to capabilities. This difference is due to the shifting of importance from the high end of the scale with the attributes to capabilities to the middle with the technologies. This allows for only the attributes with the most important applications to get the largest prioritization scores.

Table 21: Impact Mapping Scale

Descriptor	Acronym	Technology to Attributes Scale	Attributes to Capabilities Scale
Strong Positive Impact	SP	9	9
Moderate Positive Impact	MP	5	7
Weak Positive Impact	WP	1	1
No Impact	NI	0	0
Weak Negative Impact	WN	-1	-1
Moderate Negative	MN	-5	-7
Strong Negative Impact	SN	-9	-9

After the votes were converted into the quantitative scale then the multiplication of the matrices was performed to obtain the mappings of the technologies up to the capabilities. This was done separately for the surface ship and the submarine, matrices which results in separate rankings. The computed prioritization scores for all the technologies are given in Table 22. These values are the result of the matrix multiplication and have not been normalized or scaled.

Table 22: Surface Ship Technology to Capability Benefit Scores

	Speed 1	Speed 2	Speed 3	Strike 1	Strike 2	Strike 3	Strike 4	Special Operations 1	Special Operations 2	Survivability 1	Survivability 2	Survivability 3	Survivability 4	Survivability 5	Flexibility 1	Flexibility 2	Flexibility 3	Logistics 1	Logistics 2	Logistics 3	Logistics 4	Human Integration 1	Cost 1	Cost 2
SI&D 1	7.5	2.25	7.5	3.5	24.5	0	0	0	25.5	25.5	27	27.5	12.5	0.25	24.5	0.5	-2	2	15.5	7.5	-17.5	6.75	6.5	1
SI&D 2	11	8	2	14	8	0	0	0	6.5	0	0	0.5	0.5	0.5	1.75	12	4.5	13.5	11	13	-12.5	11	11	3.5
SI&D 3	2	14	2	2	2	0	0	0	5	0	0	1.5	1	18	0.5	2	17	2	0.5	2	-14	2	2	1
SI&D 4	12.5	2	12	8.5	34.5	0	0	0	47.5	46.5	9	54.5	44.5	20	46.5	7.5	-0.25	13	34.5	19.5	-58	16.5	16.5	1.5
SI&D 5	9	1	9	1	7	0	0	0	9	9	0	1	1	0	7	1	-0.5	1	7	9	-4	7	7	1
SI&D 6	9.5	4.5	9.5	1.5	7.5	0	0	0	11	9	0	1.5	1.5	4.5	7.25	1.5	3.5	1.5	7.25	9.5	-7.5	7.5	7.5	1
HF&P 1	56.5	13.25	48	19.5	46.5	0	0	0	55	48.5	4.5	10	7.5	0.5	40.25	17	1.75	18.75	48	58.5	-34.5	46.5	46.5	8.5
HF&P 2	79	22.5	68	23	72	0	0	0	86	77	9	26	20	14	65	16	5.5	20.5	65.5	82	-62	66	66	9
HF&P 3	96.5	21	85	24.5	81.5	0	0	0	95	88	9	18.5	13.5	5.5	71.75	18	0.5	21	75.25	98.5	-57.5	78.5	78.5	11
HF&P 4	60	13.5	49	20	55	0	0	0	60.5	55.5	9	18.5	13	3	47	13	-1.5	17	49	62.5	-42.5	50.5	50.5	7
HF&P 5	96	66	91	24	77	0	0	0	108.5	84.5	0	20	18	74	70	24	63	24.5	74.5	98.5	-104	78.5	78.5	13
M&S 1	63.5	42	53	36.5	58.5	0	0	0	74	55.75	9	26.5	18.5	32.5	49	33	29.75	35.5	57.5	67	-63	55	55	21
M&S 2	3	19	3.3	12.5	3	0	0	0	9.5	0.5	0	11	8	20.5	2	15	19.5	14.5	8.25	3.5	-24.5	4	3.5	10.5
M&S 3	19	58.5	11	56	24	0	0	0	55	11	9	29.75	21	31	18.25	63	55.5	64.5	50.5	22.5	-55.5	20.5	20.5	31
M&S 4	27	45.75	17	46	30	0	0	0	39.5	20	9	28.5	18	43.25	21.5	46	36.75	45	31	32.5	-45	28.8	28.5	34.5
M&S 5	6	49	6.5	13	6	0	0	0	16	0	0	5.5	3	62	1.5	15	58	13	2	7	-41	7	7	12
M&S 6	35.5	48.5	12	42.5	62.5	0	0	0	54.5	35.25	45	52	24.5	35	38.5	21	22.75	31	31.5	38.5	-99.5	39	36.5	19
M&S 7	21	47	11	44	17	0	0	0	22.5	4.5	0	5.5	2	38.5	6.25	46	42.25	43	20.25	26	-27.5	23	23	34.5
M&S 8	14.5	71.5	12	14.5	19	0	0	0	32.5	7	9	16.5	9	90.5	10	14	84.25	14	10	15.5	-84.5	15	14.5	6.5
M&S 9	16	82	17	46	18	0	0	0	64.5	6	0	60	49	91	16	51	86.5	56.5	44.5	16.5	-102	16.5	16.5	21
S&M 1	35.5	15	20	27.5	50.5	0	0	0	57	51	9	55.5	45	29.5	52.25	24	10	30.5	52.5	46.5	-84.5	38.5	38.5	5.5
S&M 2	9	4.5	9	9	63	0	0	0	63	63	81	81	36	0	63	0	-4.5	4.5	36	9	-36	9	9	0
S&M 3	60.5	5.25	13	56	52.5	0	0	0	31	12.5	4.5	3.5	3	-38.5	16	27	-33.3	40.75	35.25	67	8.5	56.5	59	3.5
S&M 4	28	37.25	7	28	29.5	0	0	0	22	4	4.5	15	10	28.5	7	8.5	20	18.75	10	29	-54.5	28.5	28	5.5
EQS 1	10	33	4.5	17	16	0	0	0	17	7	9	11.5	5	31.5	8	12	20	13.5	6	11	-87	15.5	11	20
EQS 2	29	33.5	5	29	26	0	0	0	14	0	0	0.5	0	16.5	2.5	11	8	20	10	31	-98	33.5	29	14
EQS 3	20	33	14	12	24	0	0	0	23	16	9	11.5	5	31.5	14.5	5	23.5	8.5	12	20	-85	21.5	18	12
EQS 4	8	16.5	2	8	8	0	0	0	5	0	0	0.5	0	12.5	0.5	2	7.5	5	1	8	-49	10.5	8	7
EQS 5	22	47	16	14	26	0	0	0	25	16	9	12.5	5	49.5	14.5	7	41.5	10.5	12	22	-99	23.5	20	14
V&SS 1	-35	-5	4	-35	16	0	0	0	58	63	0	81	72	36	58	-35	-2.5	-26	1	-36	-46	-26	-26	-5
V&SS 2	1	20	12	8	30.5	0	0	0	55.5	50.5	0	92	77.5	70.5	51.75	7	21.25	15	28.25	8	-90	9	9	9.5
V&SS 3	24	16	17	16	39	0	0	0	53	44	0	47	42	30	44	10	9	18	35.5	31	-70	27	27	3
V&SS 4	5	5	14	5	41	0	0	0	68	65.5	0	126	107	71	68	0	2.5	14	41	14	-116	14	14	0
V&SS 5	2	8	7	8	22	0	0	0	43	35.5	0	55	48	27	37	9	7.5	15	28	7	-56	7	7	4
V&SS 6	1	1	8	1	29	0	0	0	50	49.5	0	72	63	35	50	0	0.5	8	29	8	-70	8	8	0
V&SS 7	12	2	11	8	28	0	0	0	41	39.75	0	50	44	23.5	40	7.5	0.5	13	31	19	-57.5	16	16	1.5
V&SS 8	5.5	1.5	13	1.5	32.5	0	0	0	54.5	54	0	72.5	63.5	35	53.5	0.5	0.25	8.5	32.5	12.5	-72	11.5	11.5	0.5
V&SS 9	4.5	13.5	14	10.5	40.5	0	0	0	75	64.5	0	109.5	94.5	61.5	67.25	9.5	12.5	21.5	46.25	13.5	-110	13.5	13.5	4

Ranked Sorting

The first step in the evaluation of the technologies was to perform an individual assessment of each of the programs and analyze its benefit to the capabilities. In order to generate a single value to sort the programs an OEC was utilized which normalized the values for each capability by the sum of the squares and applied the goal importance as a weighting factor. The technologies could then be sorted based on this value or on the benefit/cost ratio, whichever the decision maker preferred. The sorted list and benefit/cost ratio for a single scenario is shown in Table 23. It should be noted that the benefit and benefit/cost ratio are nondenominational as they have been normalized with respect to the maximum value of each. This is done to make the numbers slightly easier for the decision maker to compare as well as to remove the large number of digits in order to illustrate the point that the numbers themselves have no meaning without the other technology programs.

Table 23: Surface Ship Technology Benefit and Benefit/Cost

Technology ID	Relative Benefit					Relative Benefit/Cost				
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Composite	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Composite
SI&D 1	0.361	0.180	0.239	0.174	0.234	0.183	0.091	0.097	0.105	0.115
SI&D 2	0.114	0.104	0.217	0.135	0.140	0.096	0.087	0.147	0.135	0.115
SI&D 3	0.090	0.072	0.039	0.103	0.077	0.054	0.043	0.019	0.072	0.045
SI&D 4	0.455	0.311	0.352	0.422	0.386	0.016	0.011	0.010	0.017	0.013
SI&D 5	0.061	0.072	0.079	0.052	0.067	0.281	0.328	0.291	0.282	0.297
SI&D 6	0.084	0.090	0.088	0.078	0.086	0.059	0.063	0.049	0.065	0.059
HF&P 1	0.476	0.490	0.647	0.420	0.507	0.513	0.523	0.558	0.536	0.530
HF&P 2	0.755	0.716	0.876	0.655	0.754	0.710	0.668	0.660	0.729	0.689
HF&P 3	0.801	0.807	1.000	0.676	0.825	1.000	1.000	1.000	1.000	1.000
HF&P 4	0.560	0.519	0.687	0.471	0.560	0.917	0.844	0.902	0.914	0.891
HF&P 5	0.984	1.000	0.994	0.969	1.000	0.422	0.426	0.342	0.493	0.416
M&S 1	0.802	0.760	0.970	0.786	0.810	0.269	0.253	0.260	0.312	0.263
M&S 2	0.173	0.175	0.225	0.236	0.185	0.050	0.050	0.052	0.081	0.052
M&S 3	0.727	0.658	0.951	0.798	0.733	0.084	0.075	0.088	0.109	0.082
M&S 4	0.662	0.609	0.897	0.771	0.683	0.079	0.072	0.086	0.109	0.079
M&S 5	0.337	0.296	0.241	0.416	0.311	0.160	0.139	0.091	0.233	0.143
M&S 6	0.955	0.547	0.941	0.753	0.764	0.052	0.029	0.041	0.048	0.040
M&S 7	0.484	0.492	0.761	0.637	0.542	0.182	0.183	0.229	0.283	0.198
M&S 8	0.576	0.423	0.325	0.591	0.482	0.041	0.030	0.019	0.050	0.033
M&S 9	0.806	0.769	0.786	1.000	0.813	0.074	0.070	0.058	0.108	0.072
S&M 1	0.654	0.500	0.696	0.657	0.630	0.816	0.620	0.696	0.971	0.763
S&M 2	1.000	0.447	0.589	0.447	0.609	0.422	0.187	0.199	0.223	0.249
S&M 3	0.450	0.365	0.856	0.422	0.525	0.225	0.181	0.342	0.250	0.254
S&M 4	0.408	0.280	0.450	0.425	0.384	0.622	0.423	0.550	0.769	0.569
EQS 1	0.281	0.154	0.385	0.317	0.248	0.039	0.021	0.042	0.052	0.033
EQS 2	0.244	0.124	0.486	0.310	0.267	0.035	0.018	0.056	0.053	0.037
EQS 3	0.331	0.205	0.354	0.314	0.282	0.043	0.026	0.037	0.048	0.035
EQS 4	0.083	0.030	0.151	0.114	0.081	0.011	0.004	0.016	0.017	0.010
EQS 5	0.420	0.279	0.398	0.416	0.358	0.056	0.037	0.043	0.066	0.047
V&SS 1	0.262	0.084	-0.351	0.206	0.042	0.212	0.067	-0.228	0.198	0.033
V&SS 2	0.589	0.474	0.362	0.722	0.523	0.462	0.369	0.228	0.671	0.398
V&SS 3	0.491	0.376	0.438	0.520	0.459	0.136	0.104	0.097	0.171	0.123
V&SS 4	0.651	0.510	0.373	0.794	0.584	0.543	0.422	0.250	0.785	0.473
V&SS 5	0.370	0.286	0.264	0.417	0.327	0.176	0.135	0.101	0.236	0.151
V&SS 6	0.410	0.287	0.210	0.455	0.341	0.347	0.241	0.142	0.456	0.280
V&SS 7	0.360	0.280	0.301	0.400	0.338	0.150	0.116	0.100	0.197	0.136
V&SS 8	0.440	0.323	0.249	0.481	0.374	0.340	0.248	0.155	0.440	0.281
V&SS 9	0.675	0.521	0.432	0.783	0.598	0.127	0.098	0.065	0.175	0.109

Once the ranked order was established, the funding can be allocated to the top technologies until the available budget has been exhausted. The resources were distributed until a technology program would require more funding in a year than the budget had available. Once this occurred, that program was shifted in time until either no conflict was present or the program timeframe exceeded the available time for research programs. The next program on the list is allocated resources in the same process. This allowed for the budget to be as fully utilized as possible in order to bring in less costly but also less beneficial technologies.

Two sample resource allocation funding profiles are shown in Figure 35 for a sorting by Benefit and Figure 36 for Benefit/Cost. Both of these analyses were performed for an allowable funding of $10M per year, and it should be noted that technologies which were not funded are excluded from the graph and legend. In comparing the two methods, it is evident that the Benefit/Cost provides for much better packing of programs into the allowable timeline. This is due to the tendency of the best performing technologies of this method to be of a shorter timeframe and programs with less funding per year.

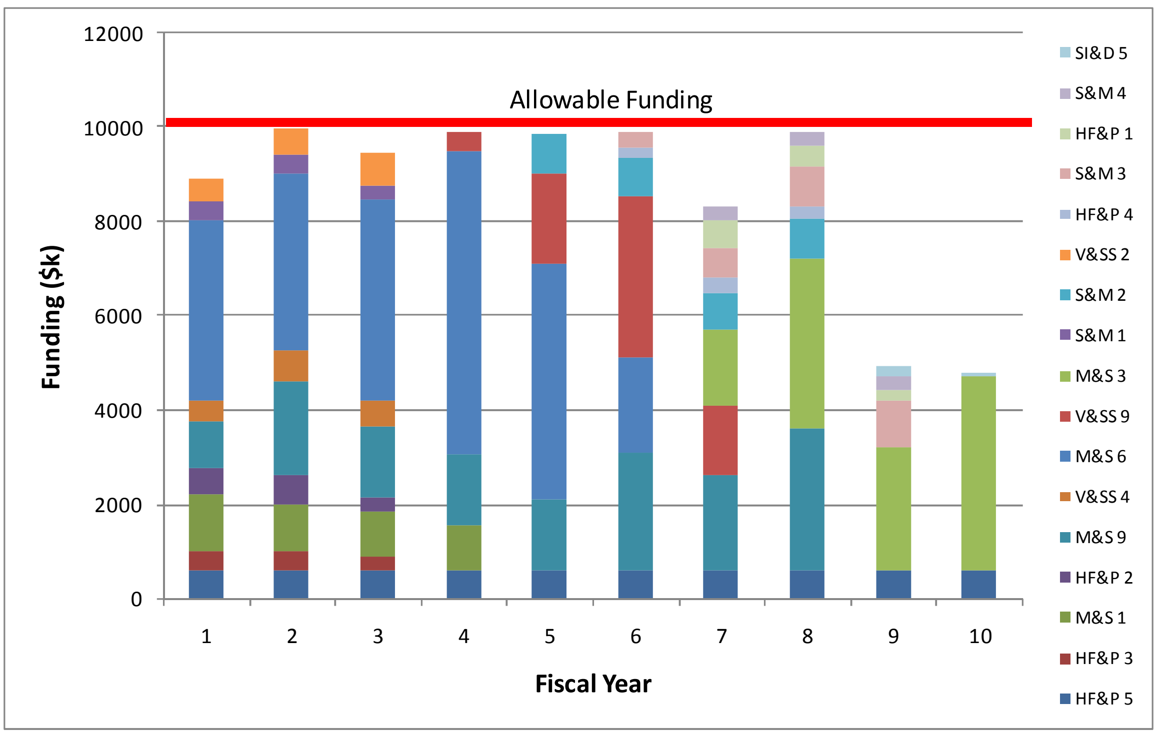


Figure 35: Sample Surface Ship Technology Resource Allocation by Benefit

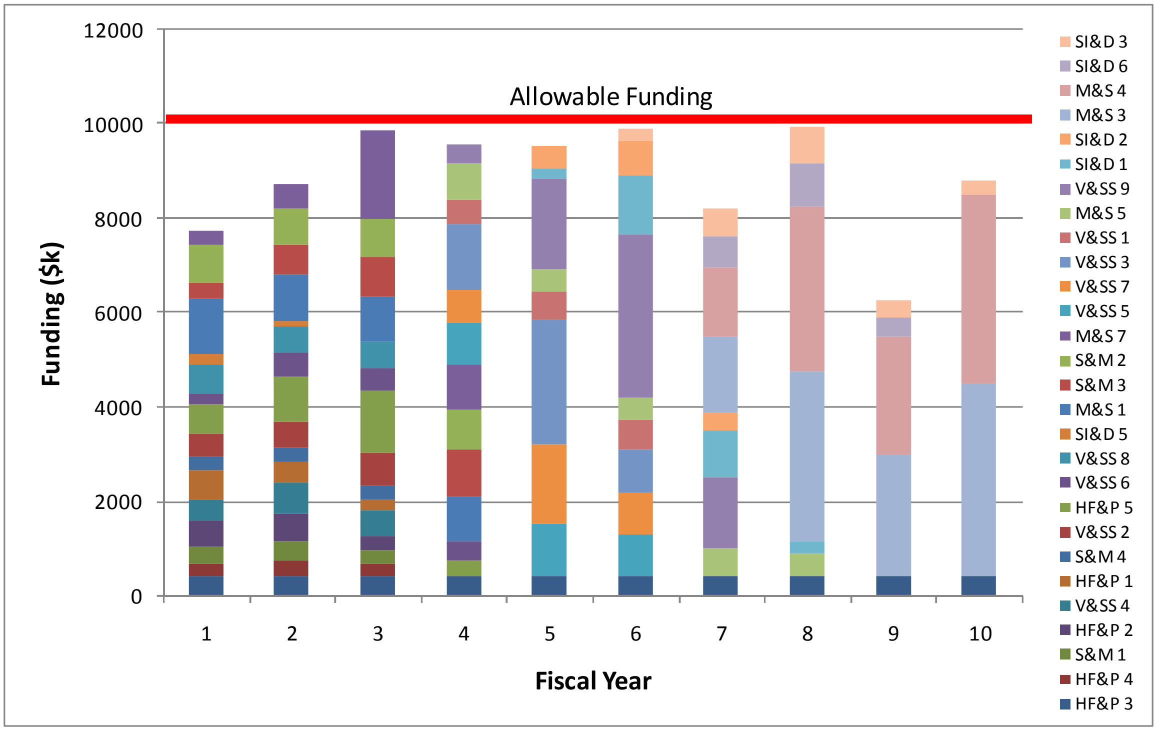


Figure 36: Sample Surface Ship Technology Resource Allocation by Benefit/Cost

Each scenario was assessed to determine the best combination of technologies which fit within the specified funding profile. The results, listed in Table 24, were used to assess trends in programs across all the potential futures. The Benefit/Cost analysis returned identical portfolios for all scenarios except 3 where the only difference was that M&S 5 was inactive. The portfolios created based on the Benefit scores always underperform the Benefit/Cost combinations in both the total benefit provided as well as the benefit/cost ratio. This would indicate that when taking into account funding profiles using the benefit/cost ratio to determine the portfolio is a better solution.

In addition to the general trends such as the best way to create a portfolio of programs, it was also possible to gain understanding on the benefit of the technologies and which would be the most robust solutions to the changing world environment. For both creation techniques the technologies SI&D 5, M&S 1, S&M 1, S&M 4, V&SS 2, V&SS 4, and all of the HF&P group were present regardless of scenario. Portfolios which contain these technologies would beneficial to the organization regardless of which of the scenarios became the dominant world outcome. It was also possible to determine that the EQS programs do not provide enough benefit to any scenario to warrant being included in a funded profile. The main reason for this was discovered to be the lack of enough direct linkages between these technologies and the overall capabilities. Due to focusing on making the ships more environmentally friendly and not a performance increase in mission capability, these programs are not beneficial. However, if a new environmental law should be enacted with the Navy must comply with, these technologies would have a greater importance due to the need to add a new capability to address this issue.

Table 24: Portfolios Selected Using Individual Program Assessment

	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Composite	
	Rank Sorting		Rank Sorting		Rank Sorting		Rank Sorting		Rank Sorting	
	Benefit	Benefit/Cost	Benefit	Benefit/Cost	Benefit	Benefit/Cost	Benefit	Benefit/Cost	Benefit	Benefit/Cost
SI&D 1		X		X		X		X		X
SI&D 2		X		X		X		X		X
SI&D 3										
SI&D 4										
SI&D 5	X	X	X	X	X	X	X	X	X	X
SI&D 6		X		X				X		X
HF&P 1	X	X	X	X	X	X		X	X	X
HF&P 2	X	X	X	X	X	X	X	X	X	X
HF&P 3	X	X	X	X	X	X	X	X	X	X
HF&P 4	X	X	X	X	X	X	X	X	X	X
HF&P 5	X	X	X	X	X	X	X	X	X	X
M&S 1	X	X	X	X	X	X	X	X	X	X
M&S 2						X				
M&S 3	X	X	X	X	X	X	X	X	X	X
M&S 4		X	X	X	X	X	X	X		X
M&S 5		X		X		X		X		X
M&S 6	X				X		X		X	
M&S 7		X	X	X		X		X	X	X
M&S 8										
M&S 9	X		X				X		X	
S&M 1	X	X	X	X	X	X	X	X	X	X
S&M 2	X	X		X		X		X	X	X
S&M 3		X		X	X	X		X	X	X
S&M 4		X	X	X	X	X	X	X		X
EQS 1										
EQS 2										
EQS 3										
EQS 4										
EQS 5										
V&SS 1		X		X				X		X
V&SS 2	X	X	X	X	X	X	X	X		X
V&SS 3		X	X	X	X	X	X	X		X
V&SS 4	X	X	X	X	X	X	X	X	X	X
V&SS 5		X	X	X		X		X		X
V&SS 6	X	X	X	X		X		X		X
V&SS 7		X		X		X		X		X
V&SS 8		X	X	X	X	X		X		X
V&SS 9	X	X	X	X			X	X		X
Benefit	1,592.63	2,039.70	1,323.43	1,459.72	1,439.20	1,703.48	1,569.61	1,994.78	1,914.71	2,557.06
Beneft/Cost	0.018	0.024	0.016	0.017	0.018	0.021	0.018	0.023	0.024	0.030

Portfolio Optimization

The Ranked Sorting methodology provided a portfolio of programs which gave the best benefit for a defined budget profile. What it did not take into account directly is the interrelationships between the technology programs. Optimization allowed for portfolios to be created that maximized the benefit to the capabilities, minimized the cost, and took into account the constraints of the interrelationships. This application used a Multi-Objective Genetic Algorithm to perform the portfolio optimization with a penalty function methodology to account for the constraints. If two incompatible technologies were included in the portfolio then the benefit scores for each were set to zero. Likewise, technologies which were included in a portfolio which did not contain their enabling program also had the benefit score zeroed out. Two synergistic technologies included in a portfolio have their benefit for every capability increased by the given factor.

The MOGA was performed in Microsoft Excel™ and written in Visual Basic and the code is included in Appendix A. A number of factors are unique to each application, and these are listed here in Table 25. The algorithm starts by generating the initial population of 100 chromosomes and assessing them for each of the 24 capabilities as well as a Benefit/Cost score. This ratio is utilized in order to bring cost into the optimization and is calculated by summing all the capability benefit scores and dividing by the total cost of each of the programs contained in the portfolio. It should be noted that while the benefit scores for incompatible technologies in a portfolio are zeroed out the costs are still included which thus degrades the Benefit/Cost score.

Selection was performed by first copying over the dominant chromosomes for each of the 25 criteria over to the next generation unmodified. This procedure ensured that the best values would be represented regardless of how the selection and crossover turned out. For the selection and crossover of the population the dominant chromosomes for each generation were given fitness values of 2 and dominated ones values of 1.5. By utilizing these values there was a 50% chance during each selection to select a dominant or an inferior members for reproduction. This allows for more genetic diversity to be introduced in each subsequent generation without eliminating the dominant genes which are carried through with the cloning procedure.

Further genetic diversity was introduced into the population through the use of mutation. Following selection and reproduction each of the resulting chromosomes was given a 15% chance of having a single bit switched. This allows for technology combinations to be introduced, which if not present in the initial population, would never have had a chance to be present. Following mutation the resulting population was set for the next generation and the process started over with the assessments of the members for dominance.

Table 25: Naval MOGA Factors

Factor	Value
Population Size	100
Number of Generations	500
Initial Seed	80506
Fitness of Dominant Chromosomes	2
Fitness of Dominated Chromosomes	1.5
Probability of Crossover	0.7
Probability of Mutation	0.15

While the elegance of a MOGA is the blending of dominant solutions in order to obtain solutions which lie upon the Pareto front, it is also necessary for the best members of the population to progress to more dominant solutions over time. Figure 37 shows the history of the MOGA for the optimization of the technology programs. This graph shows the best objective function values for every generation of the process normalized against the maximum value achieved in order to put them all on the same scale. The general trend is that significant progress is made over the first 75 generations followed by a slight plateau. It is not until around the 425th generation that the final increase is made to bring the values to their maximum values. The main outlier in this pattern is the Cost 1 objective which quickly reaches its optimum value within 10 generations.

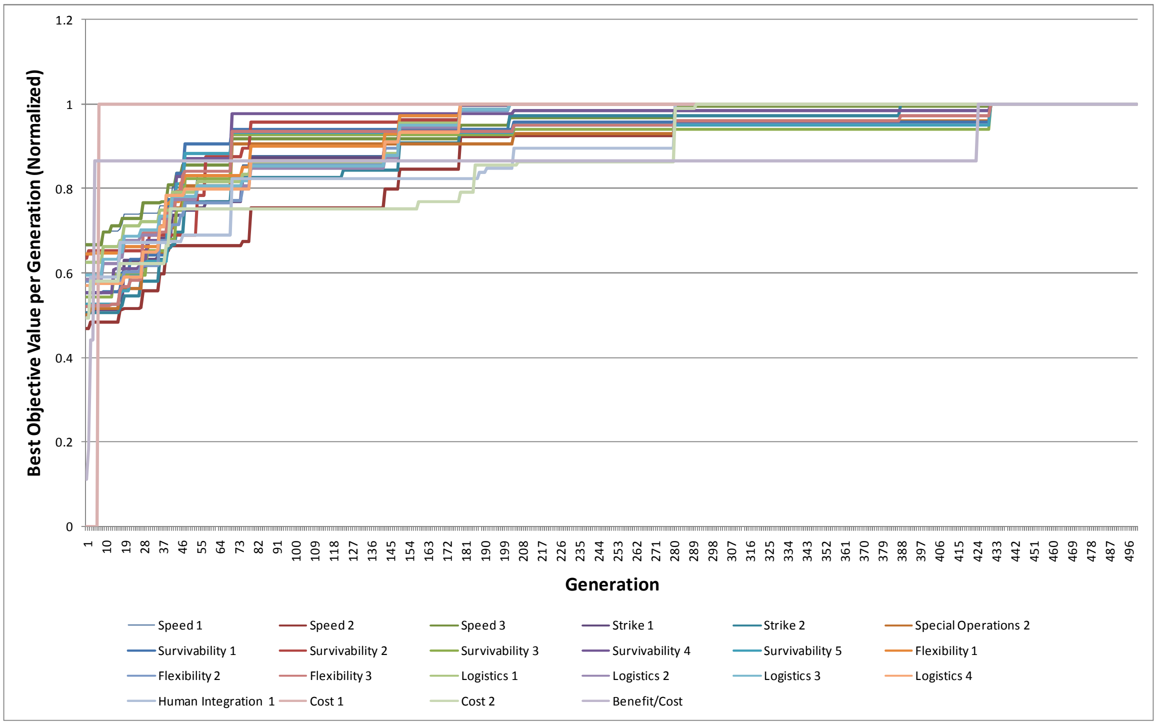


Figure 37: Optimization History of Naval S&T Program Selection MOGA

After running the MOGA and obtaining the data out of 50,100 chromosomes created and assessed, 13,336 were found to be unique. The multivariate scatterplots for these points were used to obtain trends of the technology programs and basic understanding of the interactions of the chromosomes and how they influence the results. The three unique trends which are evident are shown in Figure 38 and include the positive correlation such as that between Strike 1 and Speed 1, negative correlation like Strike 1 and Cost 1, and multiple clusters in Strike 1 and Survivability 2.

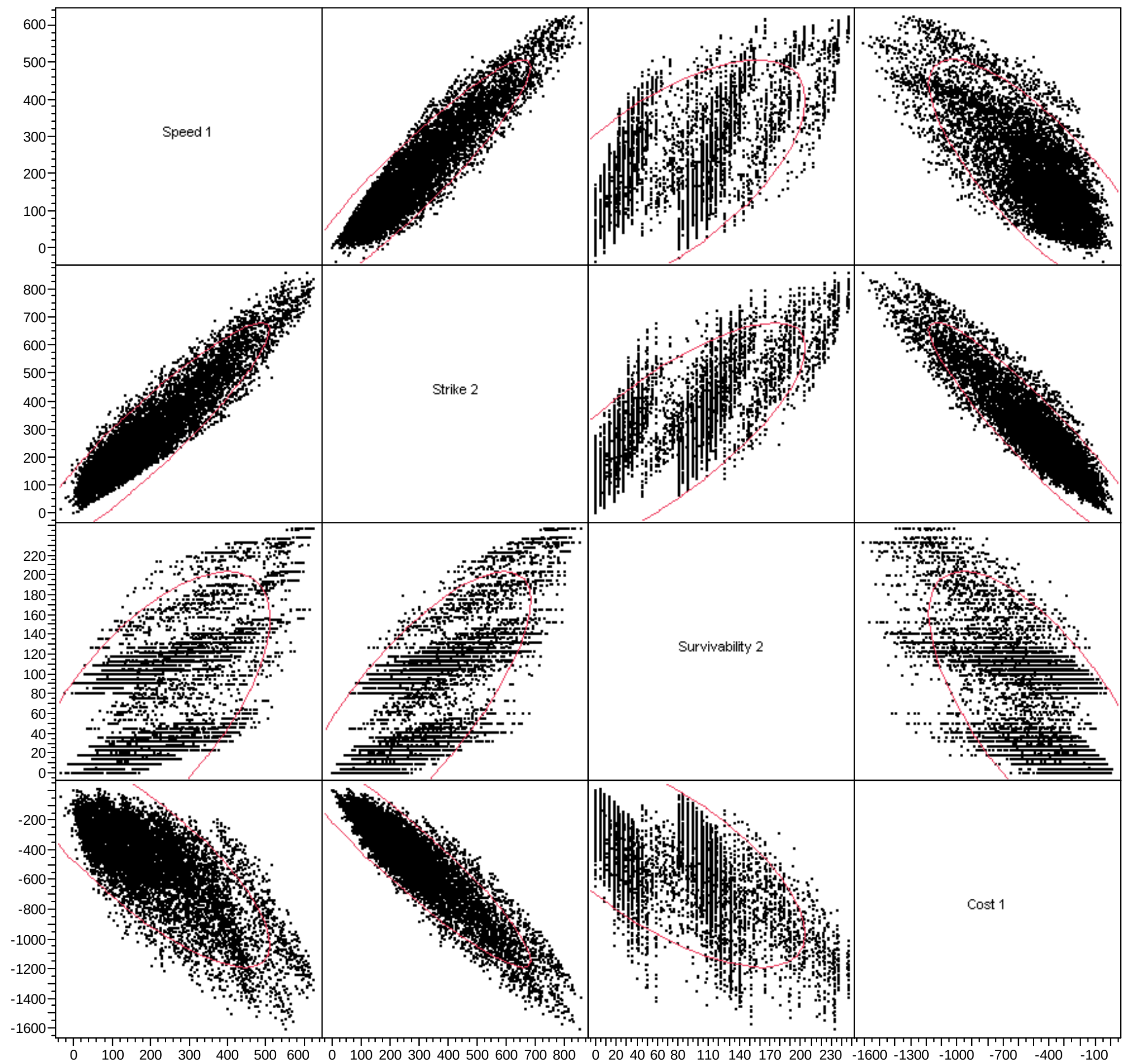


Figure 38: Multivariate Analysis for Naval MOGA Results

The clusters of values seen in Survivability 2 provided an example for understanding how the interrelationships would affect the final values. The distinct groupings which were apparent were due in part to incompatible combinations where some technologies which were beneficial for this capability were active and caused the value to increase versus the other technology being active which degraded the performance. The most influential program for Survivability 2 is S&M 2 which is incompatible with SI&D 6. This capability shows that most of this clustering is due to the minimal impact that the attributes have upon it. Referring back to Figure 33, Survivability 2 is only affected by the attribute Susceptibility which is most strongly affected by S&M 2 and M&S 6 per Figure 34. This analysis points to the interrelationships being the constraining factors that they should be for a portfolio of programs.

The best portfolio for a given scenario was determined through the use of a sorting algorithm to automatically make the selection from the 13,000 possible combinations. A graphical selection method utilizing scatterplots and brushing abilities could have been employed; however, this would have been difficult across the 25 criteria to consider. The algorithm that was selected first ranked all the chromosomes according to their total costs and eliminated all those that exceeded the total funding allowed. The remaining portfolios were sorted based on their benefit to the world scenario of interest. The portfolios were assessed to see if the funding could be fit within the selected funding profile. The benefit to world scenario capabilities for each of the optimum technology portfolios is given in Table 26. The same portfolio comes in as optimum for all the scenarios except 2 and 3 where V&SS 6 is switched for V&SS 5 and SI&D 3 is included.

Table 26: Optimum Surface Ship Technology Portfolios by Scenario

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Composite
SI&D 1	X	X	X	X	X
SI&D 2					
SI&D 3		X	X		
SI&D 4					
SI&D 5	X	X	X	X	X
SI&D 6					
HF&P 1	X	X	X	X	X
HF&P 2	X	X	X	X	X
HF&P 3	X	X	X	X	X
HF&P 4					
HF&P 5	X	X	X	X	X
M&S 1	X	X	X	X	X
M&S 2					
M&S 3	X	X	X	X	X
M&S 4					
M&S 5	X	X	X	X	X
M&S 6					
M&S 7					
M&S 8					
M&S 9	X	X	X	X	X
S&M 1					
S&M 2	X	X	X	X	X
S&M 3					
S&M 4					
EQS 1	X	X	X	X	X
EQS 2					
EQS 3					
EQS 4					
EQS 5					
V&SS 1					
V&SS 2	X	X	X	X	X
V&SS 3	X	X	X	X	X
V&SS 4	X	X	X	X	X
V&SS 5		X	X		
V&SS 6	X			X	X
V&SS 7	X	X	X	X	X
V&SS 8	X	X	X	X	X
V&SS 9					

By further analyzing the portfolio of programs which was selected for Scenarios 1 & 4 and the Composite case, a better understanding of the methodology was gained. The interrelationships between the technologies present were determined by highlighting the technologies in the incompatibility matrix and seeing if incompatibilities existed where the technology interactions occurred. For this optimized portfolio there were no incompatible technology combinations which were found to exist.

	SI&D 1	SI&D 2	SI&D 3	SI&D 4	SI&D 5	SI&D 6	HF&P 1	HF&P 2	HF&P 3	HF&P 4	HF&P 5	M&S 1	M&S 2	M&S 3	M&S 4	M&S 5	M&S 6	M&S 7	M&S 8	M&S 9	S&M 1	S&M 2	S&M 3	S&M 4	EQS 1	EQS 2	EQS 3	EQS 4	EQS 5	V&SS 1	V&SS 2	V&SS 3	V&SS 4	V&SS 5	V&SS 6	V&SS 7	V&SS 8	V&SS 9
SI&D 1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1
SI&D 2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
SI&D 3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
SI&D 4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1
SI&D 5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
SI&D 6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
HF&P 1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
HF&P 2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
HF&P 3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
HF&P 4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
HF&P 5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
M&S 1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
M&S 2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
M&S 3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
M&S 4	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
M&S 5	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1
M&S 6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1
M&S 7	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
M&S 8	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
M&S 9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S&M 1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
S&M 2	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
S&M 3	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
S&M 4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
EQS 1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
EQS 2	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
EQS 3	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
EQS 4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
EQS 5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V&SS 1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V&SS 2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V&SS 3	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
V&SS 4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V&SS 5	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V&SS 6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V&SS 7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V&SS 8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V&SS 9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 39: Incompatibility Relationships for Optimized Technology Portfolio

The same analysis was performed for the enabling technologies to determine whether any relationships were present in the portfolio which would preclude a technology be active. The matrix, shown in Figure 40, has highlighted several combinations in red where a technology was included by the enabler was not. The reasons for two of these became clear upon further inspection. These technologies whose enablers were not active were, in fact, enablers themselves for two other programs. The way the relationship determination had been made, if all the enabling technologies were included in the portfolio it was active regardless of if any the enablers were active themselves. From a physical standpoint this could be explained as the inactive enabler should still be researched in order to provide a small research objective which allows work on another project even though its own full potential is never realized. Looking at

Table 23, M&S 9 which is enabled by SI&D 1 provides the third highest capability benefit to Scenario 1 and Composite and the highest value to Scenario 4 which is why the optimizer has included the both in the optimization. The only value which is not explainable is the inclusion of M&S 5, which is not enabled and does not itself enable any other technologies. Analyzing this further would allow the planner to remove this technology in order to free up additional money for other technology programs.

	SI&D 1	SI&D 2	SI&D 3	SI&D 4	SI&D 5	SI&D 6	HF&P 1	HF&P 2	HF&P 3	HF&P 4	HF&P 5	M&S 1	M&S 2	M&S 3	M&S 4	M&S 5	M&S 6	M&S 7	M&S 8	M&S 9	S&M 1	S&M 2	S&M 3	S&M 4	EQS 1	EQS 2	EQS 3	EQS 4	EQS 5	V&SS 1	V&SS 2	V&SS 3	V&SS 4	V&SS 5	V&SS 6	V&SS 7	V&SS 8	V&SS 9
SI&D 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SI&D 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SI&D 3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SI&D 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SI&D 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SI&D 6	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF&P 1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF&P 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF&P 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0
HF&P 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HF&P 5	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M&S 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M&S 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M&S 3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
M&S 4	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M&S 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
M&S 6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M&S 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M&S 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M&S 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
S&M 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S&M 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S&M 3	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S&M 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
EQS 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EQS 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EQS 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
EQS 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EQS 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V&SS 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V&SS 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
V&SS 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V&SS 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V&SS 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
V&SS 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V&SS 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V&SS 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V&SS 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0

Figure 40: Enabling Relationships for Optimized Technology Portfolio

The Multi-Objective Genetic Algorithm brought the complex interrelationships which would be extremely difficult for a planner to utilize in manually creating a portfolio and used them to optimize a series of portfolios. While it is not recommended to use the optimizer as a substitute for analysis and human knowledge these combinations can be used to better inform and aid the user. This advancement in the methodology allows for the solving of problems which had up to this point been difficult and poorly developed.

Step 7: Create Decision Support System

Creation of the decision support system was done in Excel® due in part to the ease with which graphs and sorting algorithms can be easily integrated as well as the sponsor already having access to it without the need to purchase any additional software. In order to keep the planner focused on the task at hand and eliminate confusion, the majority of the controls and graphics were confined to just a few worksheets. Data was separated based on the complexity of the analysis in order to divide the final system into one version which would be useful from a managerial point of view and one which would be more useful to an analyst working on the underlying reasons for the interactions.

Individual Program Evaluation

Due to the separate nature of the analyses and calculations which drive the individual program evaluation and the portfolio optimization, it is necessary to have separate decision support systems. Each provides the decision maker and planner with different analyses and allows for gathering different pieces of information. The dashboard for the individual program assessment is shown in Figure 41. The overall layout is designed to compartmentalize various functions or similar displays in order to keep the eyes from having to shift around to see various trends.

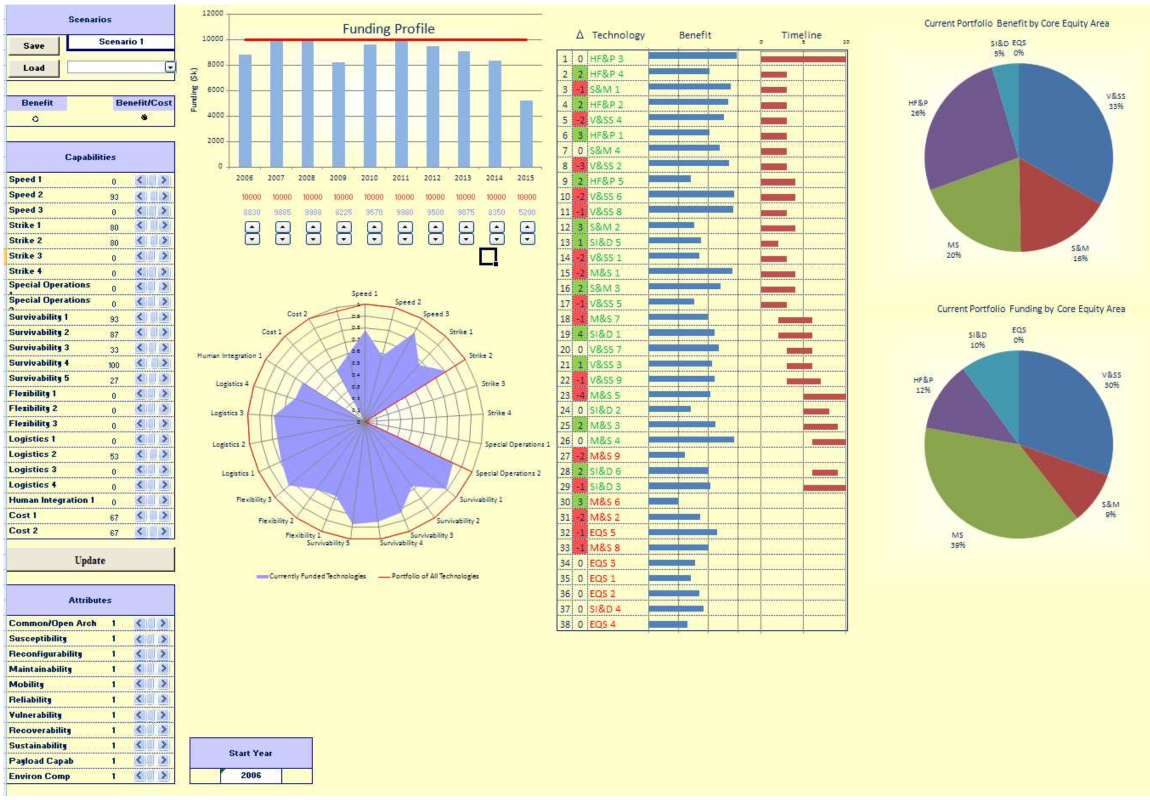


Figure 41: Decision Support System Dashboard for Individual Program Assessment

The controls area, which is highlighted in Figure 42, is the location where the user can dial in various tradeoffs and manipulate assumptions in order to determine the impact on the ranking and portfolio. The "Scenarios" section is where the user can select which of the pre-generated world scenarios is loaded into the calculation of the benefit score. In addition, the decision maker can save new scenarios from this location after altering the capability importance values or budget profile. The "Benefit" and "Benefit/Cost" selections allows for the calculations of the funding profile to be selected to utilize either of these values. The "Capabilities" area is where the importance values are displayed and where the user can adjust them based on various tradeoffs being explored. The "Update" button recalculates the funded technology portfolio based off whatever changes have been made to the controls in the dashboard. The "Attributes" section allows for weightings to be placed on any of the system level attributes or for them to be removed from the calculation process.

Figure 42: Decision Support System Controls for Individual Program Assessment

The middle area of the DSS dashboard is devoted to the information which is of most interest to the decision maker and planners. The first element is the funding profile which is illustrated in Figure 43. The red line and numbers represent the allowable budget which is currently being used in the system calculations. The user can enter these manually or use the spinner bars below to adjust them to the amount of funding that is available. The blue bars and numbers represent the amount of funding which is being used by technologies. This graph gives the decision maker an understanding of which years are constraining the funding of more technologies and how money may be moved from subsequent years in order to gain more benefit.

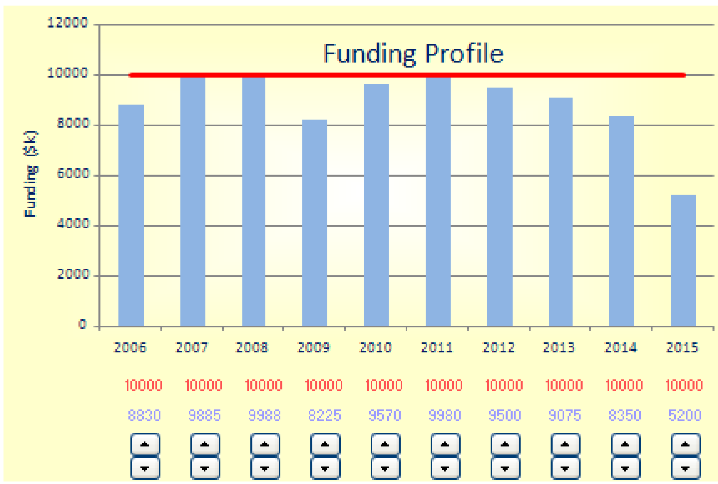


Figure 43: Decision Support System Funding Profile

In the allocation of resources to only selected technologies, there will be some loss in capability. Visualizing where these tradeoffs are occurring is the purpose behind the radargram shown in Figure 44. In this depiction the red line illustrates the maximum benefit for each capability which can be achieved by combining all the technologies into a single portfolio. The blue area represents the currently funded technologies and the benefit which results. In the example shown, the selected portfolio manages to contribute to every capability which all technologies can affect except Cost 1 which reflects the acquisition cost of the system. Nearly all of the technologies have a negative relation with this capability because adding complexity to the system in the form of new technologies will inevitably drive the acquisition price up.

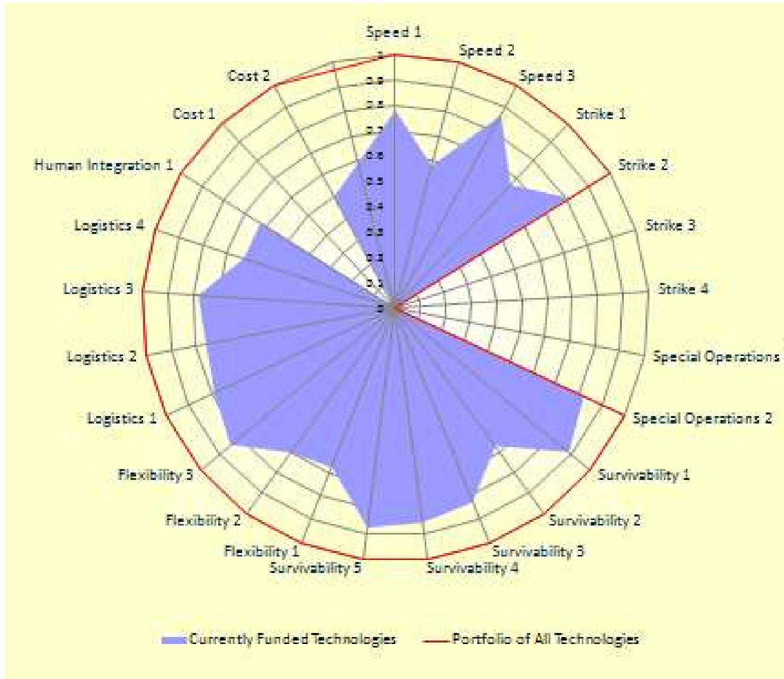


Figure 44: Decision Support System Radargram

The comparison of the individual technologies allows the decision maker to understand not only what the final ranking of the programs resulted from the funding algorithm but also why those occurred. This listing, shown in Figure 45, lists all the programs from the highest ranked to the lowest based on either the total benefit score or the benefit/cost score. The first graph to the right of the data list is abr chart which shows the benefit scores of the technologies. The next chart is the timeline of the funded programs and shows when each technology is slated to start and the duration of the research.

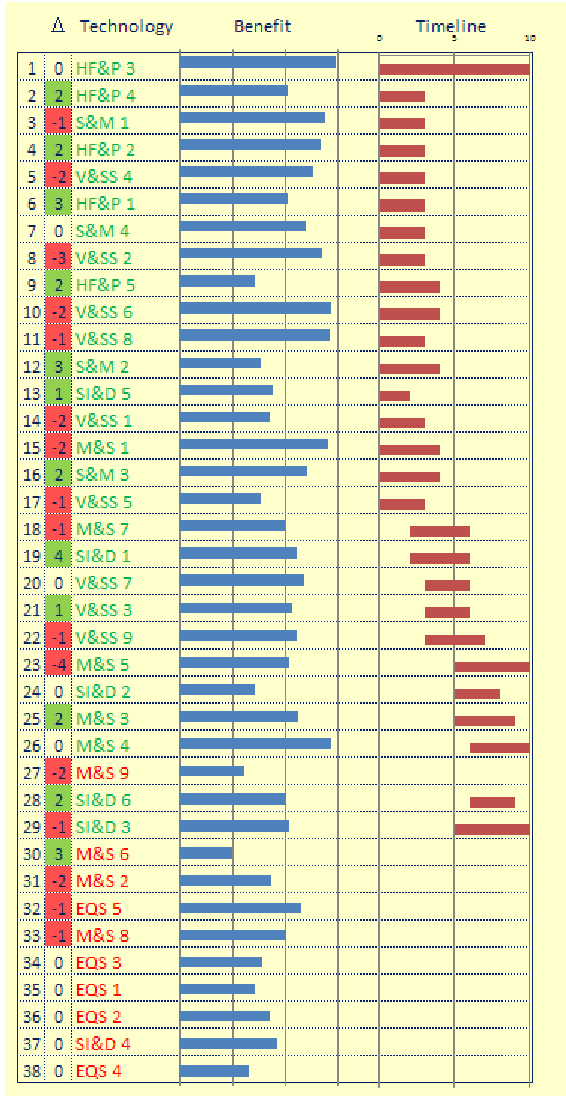


Figure 45: Decision Support System Individual Technology Evaluation

The final piece of the individual program assessment is the portfolio assessment area which shows the secondary information which a decision maker must take into account in order to make informed funding decisions. For the purpose of this demonstration, the portfolio examination shown in Figure 46 shows how much of the funded technologies fall into the Core Equity Areas. The areas of these two pie charts are weighted based on the benefit for the top one and funding for the bottom. The results indicate that HF&P and S&M Core Equity Areas provide more benefit for the portfolio than they do funding. The opposite is true for the MS and SI&D areas which make up much less of the benefit score than they do the total portfolio funding. This analysis is useful to the final decision maker allocating funds to the different divisions and playing the political games that inevitably go with resource allocation and strategic planning.

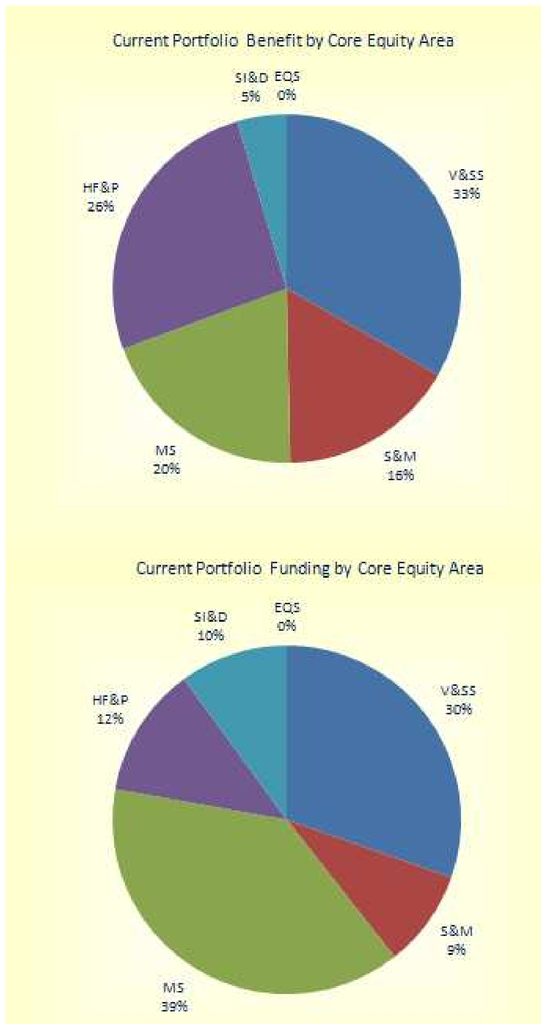


Figure 46: Decision Support System Portfolio Visualization for Individual Assessment

Portfolio Optimization

The DSS for the portfolio optimization visualization is similar in design to the Individual Program Assessment. The difference in function is that for this methodology a selection is being made amongst portfolios rather than individual technologies. The frontend of this planning and resource allocation tool is shown in Figure 47. The controls are very similar to those for the individual program assessment with the only difference being the removal of the benefit and benefit/cost selection option. This is due to the selection of portfolios which is based purely on the benefit rather than the selection of technologies based on either one of the two factors.

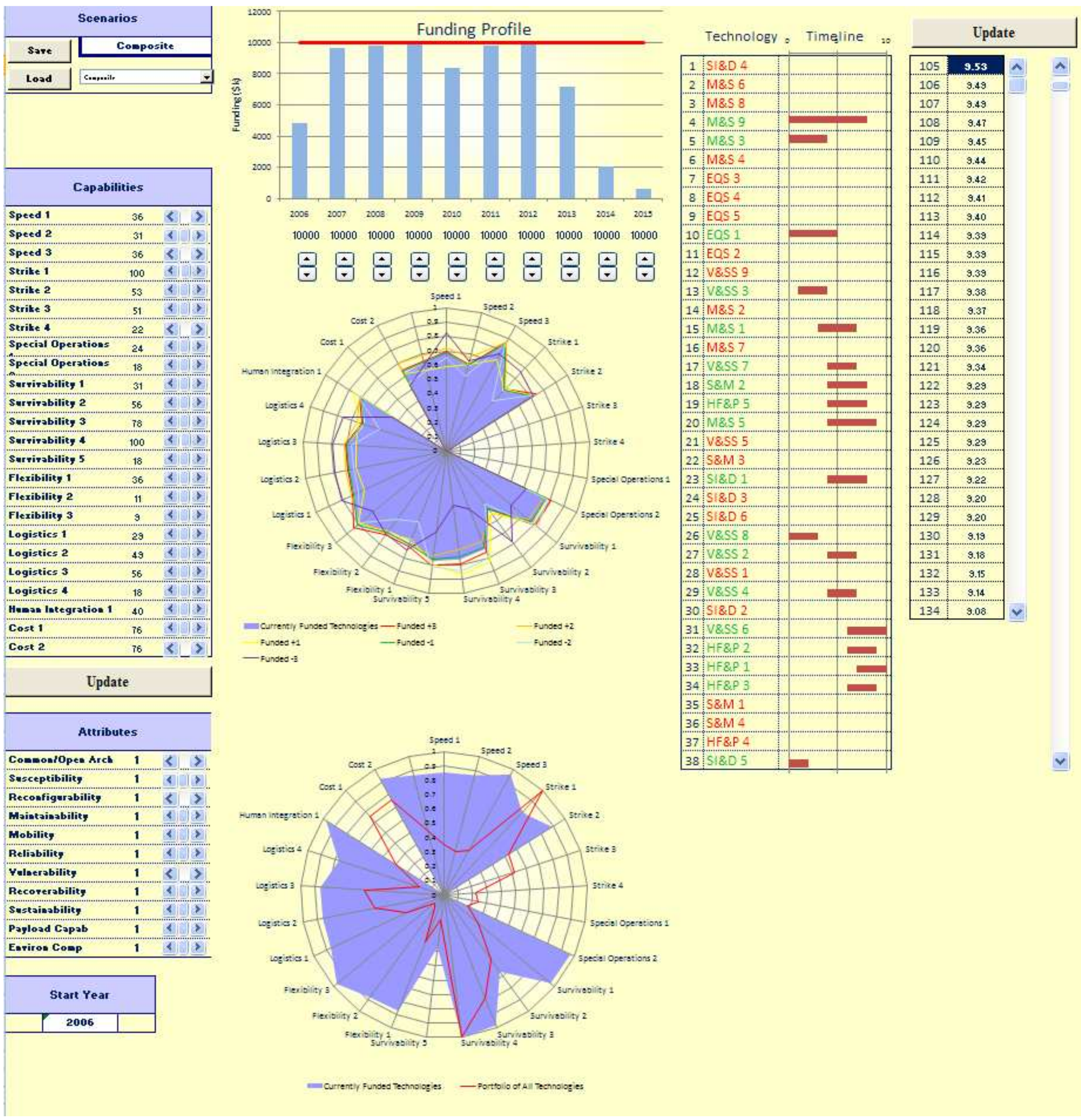


Figure 47: Decision Support System for Portfolio Optimization

The comparison of different portfolios is a crucial step in the planning and resource allocation process. The graphs shown in Figure 48 were created to facilitate this decision making process by giving the planner a collection of different information. The top radargram shows the amount of benefit which the portfolio provides with the full area representing the maximum values which were obtained in the optimization for all the objectives. The blue area is representative of the current optimized portfolio or one which has been manually selected. The lines on this represent other portfolios which rank near the currently selected one. The red, orange, and yellow are those portfolios which 3, 2, and 1 place higher respectively than the current one. The green, blue, and violet lines are the three portfolios which are of slightly lower rank. This comparison allows the decision maker to determine whether a there is much difference in the final benefit than the current one.

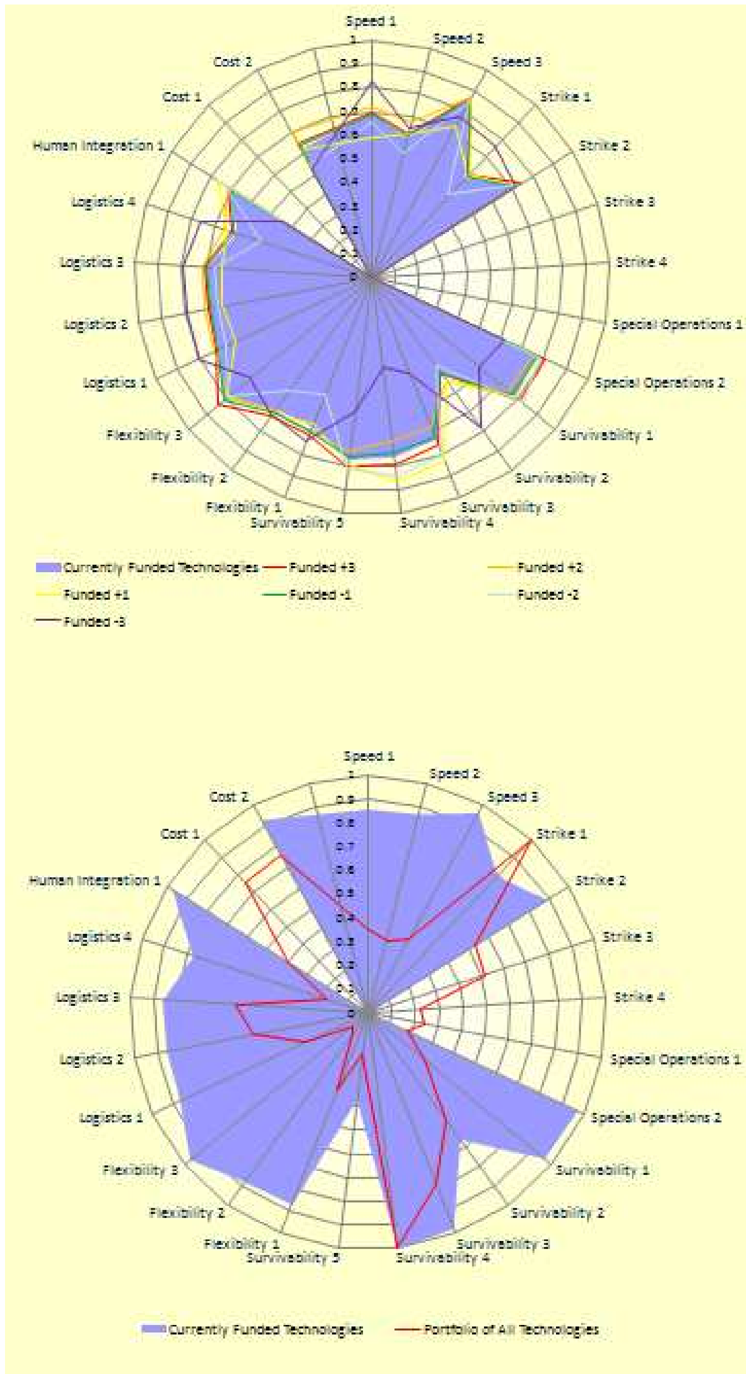


Figure 48: Decision Support System for Portfolio Comparison and Evaluation

The lower radargram in Figure 48 represents the preferences specified by the decision makers in the capabilities control area or those loaded from a certain scenario with the red line. The blue area shows the current portfolio relative benefit amongst the capabilities. This chart is aimed at showing the decision maker how their preferences match up against the programs actually funded but should not be used to determine whether quantitative requirements on the capabilities are being met. Because qualitative relationships were created it is not possible to make quantitative judgments based on the final benefit values. The main feature of interest is determining whether the shape of the area is comparable to the shape of the capability preferences. This alignment would illustrate that the programs within the portfolio are well aligned with what the decision maker needs in order to advance the organization vision.

The individual program comparison shown in Figure 49 is very similar to that shown in the individual program assessment. The programs are listed and highlighted red for those which are not included in the portfolio and green for those that are. The timelines of funding for the programs are shown to the right of the technology name. The list to the right of the technologies is all the portfolios generated by the MOGA along with their corresponding benefit value for the specified scenario. The slide bar to the far right allows the user the scroll amongst all the possible portfolios, and the slide bar adjacent to the values allows for the selection on a specific one. If a new portfolio is selected, the user can press the Update button to attempt to fit that portfolio within the specified funding profile. If the programs cannot be fit within the profile then the minimum deviation will be shown for the user to make funding decisions which may bring it within the allowable values.

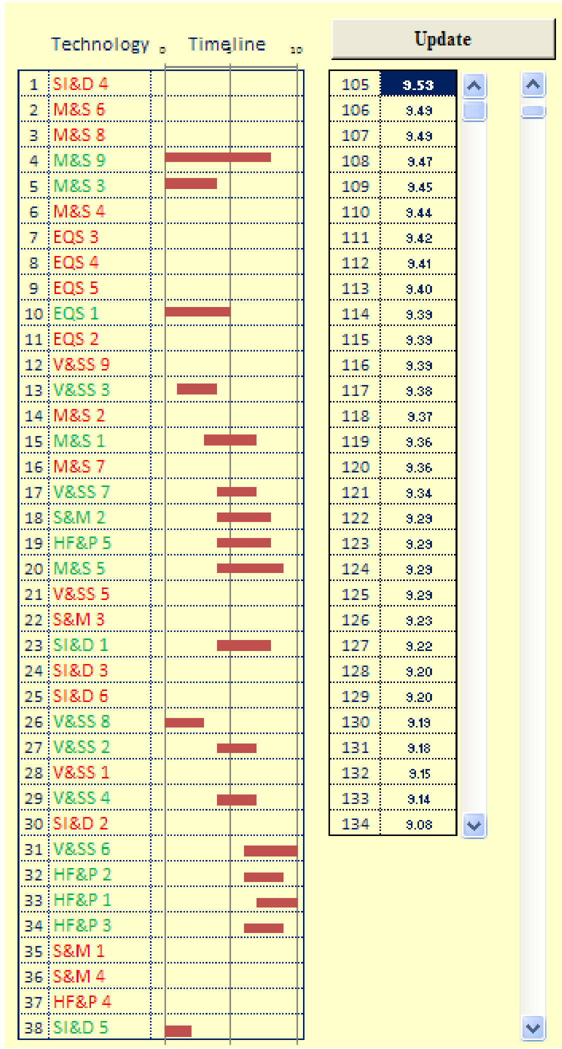


Figure 49: Program Evaluation and Portfolio Selection

This decision support system was created as an example for the NAVSEA science and technology resource allocation and strategic planning exercise. The visualizations are examples of the types which a decision maker may be interested in seeing, but adaptation and tailoring are required for every application. Iteration is especially important in the creation of the decision support system as questions are asked by the planners which need to be addressed with a graph or control on the information model. With a well constructed problem and comprehensive methodology all the information needed to answer the questions will be present and available to be placed on the frontend in some fashion.

Step 8: Make the Decision

With the decision support system created and refined with the help of the decision maker, it is possible for the planners to utilize this tool in order to decide which programs should be funded to maximize the vision of the Navy. It should not be forgotten that the SOAR methodology is a process for creating decisions and allocating resources strategically rather than just the resulting software front end. With a structured vision decomposition, the plans which are visualized have direct application to the where the organization wants to go. The information on these technologies was collected through a rigorous questionnaire, and elicitation scheme which allows the decision maker to understand all the secondary implications which are present in selecting some programs over other. The connections of the levels of the hierarchy were created through a traceable and accountable process of soliciting the opinions of the decision makers. With all these elements the strategic planner can be assured that the final decision will be comprehensive and still retain a simplicity which allows for easy understanding.

CHAPTER 6

CONCLUSIONS

The global marketplace has become much smaller with companies from around the world competing against each other in new markets. In addition to corporate competitions governmental agencies are requiring increased accountability for funding especially that dealing with science and technology. Both situations require day to day programs to be linked to the vision of the organization in order to ensure that the maximum benefit is obtained for the allocated funding. Strategic planning is the methodology of creating large scale business plans which encompass the activities of the company or agency in order to consolidate activities.

Strategic planning involves taking the vision of the organization which is the direction the management wants for the future and directly links this to the day to day activities. The creation of this plan requires a decomposition of the organization hierarchy in order to allow for relationships to be created. By utilizing this decomposition the programs and activities of the company can be directly related to the vision in order to establish the benefit which they bestow. In the absence of infinite resources it is necessary to prioritize these programs in order to allocate resources, to those which give the greatest benefit to the organization.

Strategy Optimization for the Allocation of Resources (SOAR) provides a comprehensive process which integrates the features of strategic planning into a single methodology. By utilizing Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis, the vision can be created and top level goals identified which take advantage of the characteristics of the organization. These goals can then be prioritized based on world scenarios which are created to model the possible future uncertainty of the world environment. By decomposing the organization from the top level goals to the proposed programs, relationship matrices can be established. These frameworks are qualitative connections which are decided by a group of Subject Matter Experts in a voting workshop utilizing the Nominal Group Technique. Once these are established the program benefit to the goals can be quantified, and a ranking of the programs created. Since interrelationships between the programs may exist, the need to create an optimum portfolio which takes these into account is needed. Utilizing a Multi-Objective Genetic Algorithm takes the constraints of incompatibilities, enablers, and synergistic technologies into account in the creation of portfolios which optimize the various top level goals of the organization. Finally, creating a Decision Support System allows for the information obtained in the process to be displayed to the decision maker in such a way as to make plans and resource allocation more informed.

In order to address the lack of solid vision creation in existing strategic planning methodologies SOAR utilizes the Strengths, Weakness, Opportunities and Threats analysis combined with brainstorming techniques. By identifying the elements of the organization which have the most impact on the achievement of the vision, the organization can create a measure of the effectiveness of the programs. For the example Naval S&T application the use of high level vision documents and the creation of world scenarios to address potential opportunities and threats successfully captured the needed big picture view of what capabilities were required.

The prioritization of the goals to the world scenarios was an area which has had a great influence on the results of the program sorting and prioritization in previous applications. An insufficient amount of research has been conducted to address which methodology provided the decision maker with the best ranking for the amount of time and funding available. The proposed methodology highlighted two separate techniques which were applicable depending on the scope of the problem. Pairwise comparison is useful when the number of goals and world scenarios is small enough that the gathering of the participants is possible. Cumulative voting is a simpler process which does not provide as strong a relative prioritization as the pairwise but can be accomplished in a fraction of the time. The Naval application had a total of 24 goals and 4 world scenarios which required the use of the latter method due to the limited availability of the workshop participants. This voting technique proved to be acceptable for this use and provided results which clearly ranked the goals according the priorities placed on them by the high level managers.

The determination of appropriate sample sizes is an issue which had plagued both the goal prioritization as well as the determination of hierarchy relationships. SOAR utilizes a sample size calculation to get the appropriate number of voters necessary to keep the margin of error within acceptable limits. After the voting has been accomplished the actual standard deviation can be computed for the sample size and revotes occur for those which fall outside of the margins. In the Naval application this critical analysis was performed to determine the quality of the voting samples, but the iteration piece was not due a loss of connection with the workshop participants. A worthy piece of future work would be to perform greater research in to the convergence of these voting samples with new votes and whether the margin of error is directly based on the fidelity of the questions.

Performing large subject matter expert information gathering was an area where more understanding was needed to determine whether resources were being used in an efficient way. SOAR contains a collection of three distinct methods for capturing group opinion based on an organization’s capability for bringing these experts together and the amount of time available for the relationship determination. The example problem agency had ample time to conduct workshops so the use of the Nominal Group Technique was selected to make use of the in person meetings for discussion and ensuring common knowledge amongst the participants. This process proved very effective in answering the questions of those involved in such a way as to ensure commonality within the group. The Delphi Technique and Online Questionnaires were not attempted in this application and would be suitable components for future work in this area.

Program interrelationships of incompatibility, enabling programs, and synergies were areas that had always been talked about in past applications but never fully utilized due to a lack of a methodology available to take full advantage of them. SOAR utilizes a Multi-Objective Genetic Algorithm to optimize a portfolio in the presence of these constraints. The elegance of the MOGA construction is in the ability to not only optimize portfolios which maximize the various objectives, but that it also allows for portfolios to be created which lie along the Pareto front in such a way that they represent the best tradeoffs amongst the criteria. The Navy S&T example utilized this methodology to take into account the technology connections and create a suitable cluster of technologies. All of these points could be easily and quickly queried by the decision maker to allow for the rapid tradeoffs of criteria to find the portfolios which created the greatest benefit at an acceptable cost.

During the application it was discovered that extremely complex interrelationships can provide difficulties in the analysis. In order to properly address these issues a full understanding of not just what incompatibilities or enablers are present but also the nature of these connections. An incompatibility of whether the final products of the programs can work together is a different problem than one which precludes the possibility of the programs being researched at the same time. Classifying these different types and further decomposing the method for addressing them separately would be a worthy future endeavor.

The use of Decision Support Systems allows the planner and decision makers to have the information obtained throughout the process placed in a single useable environment for tradeoffs and planning to occur. The SOAR methodology makes significant use of this concept by creating background models of the data which are hidden from the user but the results of which are easily accessible on the front end. Through iteration with those who must allocate the resources a DSS can be created which meets the needs and answers the questions in such a way that traceability and dynamic interaction greatly increase the understanding and integrity of the solution.

In the course of this work substantial improvement was made to the field of aerospace engineering and in particularly to decision making processes. In addition to the overall methodology which was developed, many of the constituent techniques were new applications or transfers from other fields. Chief among these benefits was the use of the interrelationships and the ability to take these into account when evaluation various technology benefits. In previous applications these incompatibilities, enablers and synergistic relationships were ignored due to an inability to compensate for them. Utilizing the improvements in the methodology contain with this thesis that is no longer the case.

Recommendations for Future Work

This work reflects the methodology which was capable of being tested and evaluated at the time of writing. Applying various aspects of the process requires the applicable real world experiment to present itself in an appropriate circumstance. For example, the testing of the pairwise comparison methodology was not possible as no problem was presented to which it adequately fit. This section will outline the possible future work recommendations which should be pursued should the applicable situation arise.

In the SOAR methodology which was proposed and tested, the results of the voting for the goal prioritization and the hierarchy relationships were taken as the median of the sample voting distribution. However, this procedure neglects to capture the uncertainty which surrounds the values due to the differences of opinion which exist amongst the subject matter experts. Modeling the distribution as a stochastic process would provide greatest benefit to the entire methodology by allowing for the uncertainty associated with the voting distributions to be fully implemented in the program evaluation process.

The sampling size calculations which are performed in order to determine the appropriate number of SME's for a voting session depend greatly on the estimates of the standard deviation. Since this proof of concept was the first application of this technique to the methodology, these estimates were based on literature searches and simple calculations. As the use of this equation evolves, it would be extremely beneficial to keep track of the actual standard deviations which result from various samples in order to further refine future assessments. Of particular interest would the correlation between the sample distributions and the vagueness of the question being asked. It would logically follow that the more subjective the relationship being obtained, the greater the variance of the responses. Proving the truth of this postulate would allow the planner to better estimate the number of people necessary to achieve a certain margin of error in the results.

Instead of a program having a single value for a relationship, utilizing a Monte Carlo analysis would allows for all the possible values which were voted on by the decision makers to be assessed in the evaluation process. This process could potentially make use of the beta distribution which was identified for use in testing the adequacy of voting results. In a stochastic sense, these distributions could also be used as the inputs into the Monte Carlo analysis to represent the voting samples. Comparing all of the possible program benefit scores would allow the decision maker to visualize not only which ones had a greater impact but also the probability of each having certain values. This analysis would allow the decision maker to create a more robust portfolio of programs which has less uncertainty as to the final impact of programs to the attributes in the hierarchy.

Another aspect of the methodology which would be enhanced through the use of stochastic modeling is the prioritization of the goals to the world scenarios. These importance values represent a high degree of subjectivity on the part of the voters and, as such, have a great deal of uncertainty associated with them. Allowing these values to be varied through the use of probabilistics would allow for the possible futures associated with the world scenarios to be better understood and planned for. This would result in a portfolio of programs which was more robust to the possible future environment.

Indeed, probabilistic analysis would even be greatly beneficial to the secondary program information which was provided in Step 4 through the use of questionnaires provided to the program managers. A significant amount of uncertainty can surround the budget profiles and schedules of the individual program. Allowing for these to be modeled and applied to a Monte Carlo analysis depending on the degree to which they may vary would allow the decision maker to identify a portfolio of programs which had quantified uncertainty in the final funding profile.

APPENDIX A

MULTI-OBJECTIVE GENETIC ALGORITHM COMPUTER CODE

```
Sub MOGA()
Application.ScreenUpdating = False
NumGen = 500
NumPop = 100
NumCriteria = 25
Numtechs = 38
Dim Pop(1 To 100, 1 To 38) As Single
Dim Obj(1 To 100, 1 To 25)
Dim BestObj(1 To 25)
Dim BestChrom(1 To 25, 1 To 38)
Dim BestMember(1 To 25)
Dim fitness(1 To 100)
Dim probability(1 To 100)
Dim CrossPop(1 To 100, 1 To 38)
Sheets("Data").Cells(1, 36).Value = Time
Randomize (80506)
'Generate Population
For Count1 = 1 To NumPop
   For Count2 = 1 To Numtechs
      Pop(Count1, Count2) = Round(Rnd(), 0)
   Next Count2
Next Count1
For Count = 1 To 25
   BestObj(Count) = -9999999
Next Count
Sheets("Chromosomes").Range(Cells(1, 1), Cells(NumPop, 38)).Value = Pop

'Begin Generations
For Gen = 1 To NumGen
   'Get Objective Values
   For Member = 1 To NumPop
      For Bit = 1 To Numtechs
         Sheets("Test").Cells(7, 1 + Bit).Value = Pop(Member, Bit)
      Next Bit
      For Criteria = 1 To NumCriteria
         Obj(Member, Criteria) = Sheets("Test").Cells(154 + Criteria, 3).Value
         If Gen = 1 Then
            Sheets("Chromosomes").Cells((Gen - 1) * (NumPop) + Member, 38 +
Criteria).Value = Obj(Member, Criteria)
```

```
            Else:  Sheets("Chromosomes").Cells((Gen - 1) * (NumPop) + (Gen - 1) +
Member, 38 + Criteria).Value = Obj(Member, Criteria)
            End If
            If Obj(Member, Criteria) > BestObj(Criteria) Then
               BestObj(Criteria) = Obj(Member, Criteria)
               BestMember(Criteria) = Member
               For Count = 1 To 38
                  BestChrom(Criteria, Count) = Pop(Member, Count)
               Next Count
            End If
         Next Criteria
      Next Member
      For Criteria = 1 To NumCriteria
         Sheets("Data").Cells(Gen, Criteria).Value = BestObj(Criteria)
      Next Criteria
      'Selection
      Sumfitness = 0
      For Member = 1 To NumPop
         fitness(Member) = 1.5
         For Criteria = 1 To NumCriteria
            If Member = BestMember(Criteria) Then
               fitness(Member) = 2
            End If
         Next Criteria
         Sumfitness = fitness(Member) + Sumfitness
      Next Member
      For Member = 1 To NumPop
         fitness(Member) = fitness(Member) / Sumfitness
      Next Member

      'Reproduction
      probability(1) = fitness(1)
      For Member = 2 To NumPop
         probability(Member) = probability(Member - 1) + fitness(Member)
      Next Member
      For Member = 1 To NumPop / 2
         Count = 0
         Mate = Rnd()
         Do
            Count = Count + 1
         Loop While Mate > probability(Count)
         Parent1 = Count
         'For test = 1 To 38
         '    Sheets("Sheet1").Cells(1, test).Value = Pop(Parent1, test)
         'Next test
```

```
   Count = 0
   Mate = Rnd()
   Do
      Count = Count + 1
   Loop While Mate > probability(Count)
   Parent2 = Count
   'For test = 1 To 38
   '    Sheets("Sheet1").Cells(2, test).Value = Pop(Parent2, test)
   'Next test
   crossrand = Rnd()
   For Count = 1 To Numtechs
      CrossPop(Member, Count) = Pop(Parent1, Count)
      CrossPop(Numtechs / 2 + Member, Count) = Pop(Parent2, Count)
   Next Count
   If crossrand > 0.3 Then
      bitcross = Round(1 + (Numtechs - 1) * Rnd())
      lengthcross = Round(1 + (Numtechs - 1) * Rnd())
    '   Sheets("Sheet1").Cells(3, 1).Value = bitcross
    '   Sheets("Sheet1").Cells(3, 2).Value = lengthcross
      If lengthcross + 1 > Numtechs - bitcross Then
         For Count = 1 To bitcross + lengthcross - 1 - Numtechs
            CrossPop(Member, Count) = Pop(Parent2, Count)
            CrossPop(Numtechs / 2 + Member, Count) = Pop(Parent1, Count)
         Next Count
         For Count = bitcross To Numtechs
            CrossPop(Member, Count) = Pop(Parent2, Count)
            CrossPop(Numtechs / 2 + Member, Count) = Pop(Parent1, Count)
         Next Count
      Else
         For Count = bitcross To lengthcross
            CrossPop(Member, Count) = Pop(Parent2, Count)
            CrossPop(Numtechs / 2 + Member, Count) = Pop(Parent1, Count)
         Next Count
      End If
   End If
   'For test = 1 To 38
   '    Sheets("Sheet1").Cells(4, test).Value = CrossPop(Member, test)
   '    Sheets("Sheet1").Cells(5, test).Value = CrossPop(Numtechs / 2 + Member, test)
   'Next test
Next Member

'Mutation
For Count = 1 To NumPop
   mutate = Rnd()
   If mutate > 0.85 Then
```

```
        mutbit = Round(1 + (Numtechs - 1) * Rnd())
        If CrossPop(Count, mutbit) = 0 Then
          CrossPop(Count, mutbit) = 1
        Else: CrossPop(Count, mutbit) = 0
        End If
      End If
    Next Count
    For Count = 1 To 100
      For Count2 = 1 To 38
        Pop(Count, Count2) = CrossPop(Count, Count2)
      Next Count2
    Next Count
    For Count = 1 To NumCriteria
      For Count2 = 1 To Numtechs
        Pop(Count, Count2) = BestChrom(Count, Count2)
      Next Count2
    Next Count
    Sheets("Chromosomes").Range(Cells(Gen * (NumPop) + Gen + 1, 1), Cells(Gen *
(NumPop) + Gen + NumPop, 38)).Value = Pop
Next Gen
    For Member = 1 To NumPop
      For Bit = 1 To Numtechs
        Sheets("Test").Cells(7, 1 + Bit).Value = Pop(Member, Bit)
      Next Bit
      For Criteria = 1 To NumCriteria
        Obj(Member, Criteria) = Sheets("Test").Cells(154 + Criteria, 3).Value
        If Gen = 1 Then
          Sheets("Chromosomes").Cells((Gen - 1) * (NumPop) + Member, 38 +
Criteria).Value = Obj(Member, Criteria)
        Else: Sheets("Chromosomes").Cells((Gen - 1) * (NumPop) + (Gen - 1) +
Member, 38 + Criteria).Value = Obj(Member, Criteria)
        End If
        If Obj(Member, Criteria) > BestObj(Criteria) Then
          BestObj(Criteria) = Obj(Member, Criteria)
          BestMember(Criteria) = Member
          For Count = 1 To 38
            BestChrom(Criteria, Count) = Pop(Member, Count)
          Next Count
        End If
      Next Criteria
    Next Member
Sheets("Data").Cells(1, 37).Value = Time
End Sub
```

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